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S103 discovering science

Note that there is no book associated with this block. The block consists of the Study File and three booklets of 'offprints' from scientific journals and other articles. It also provides a focus for a major part of your end-of-course assessment (ECA).

Study Guide for Block 12

This final block of S103 addresses two questions that have been of widespread interest throughout human history:

- how did life begin on Earth?
- is there life elsewhere in the Universe?

In addressing these questions we will go as far as we can with the present level of understanding in the scientific community, and we will also indulge in some speculation. In this interdisciplinary area we will need to draw upon a wide range of material from earlier blocks, and so you will be able to revise, consolidate, and extend many scientific concepts and skills that you have encountered before.

The origin of life on Earth, and the search for life elsewhere in the Universe, are fast-moving areas of enquiry, with exciting discoveries coming thick and fast. Therefore, rather than providing a bound book as we have for the other 11 blocks of *Discovering Science*, we have put all the printed material for this block in the Study File to facilitate updating. As well as there being no book, this block is also unusual in the extent of its reliance on previously published articles. These articles have been taken from the scientific press, and were not written specifically for S103 students. It is an important skill to be able to extract information from such articles, and you are given some advice about how to do this in Section 1 of the Study File.

We have used the study of Block 12 as a focus for a major part of your end-of-course assessment (ECA). While Part I of the ECA consists of short questions that assess your generic scientific skills, the question you are asked to complete in Part II of the ECA requires you to write a scientific account that is related to Block 12. Note, however, that only some of the marks of the account relate to your understanding of the scientific material in Block 12 (and to being able to pick out relevant information from the block). The remaining marks are awarded for your writing skills. Being near the end of the course, your account will be a culmination of the development of your writing skills, and it is appropriate that a major component of the ECA reflects this. It is important that you look at Part II of the ECA *before* you start to study Block 12, so that you know what is expected of you when you have completed the block, and so that you can make relevant notes as you are studying. Note that the ECA is the 'examinable' component of S103 and so will not be marked by your own tutor, and you will not receive detailed feedback on your performance. If you feel that your performance in the ECA has been affected by *serious circumstances beyond your control*, you should submit an E39P special circumstances form for consideration by the S103 Examinations and Assessment Board.

The study plan overleaf shows the various components of Block 12, and it includes rough estimates of the times that will be required for each section. These estimates add up to 17 hours, rather than the normal 20 hours for a two study week block. This is so that you will have time to do some work on Part II of the ECA during the two weeks allotted for the study of this block. However, if you have chosen to omit study of any of the material assessed in TMAs 06–09, you should consider reading some of the articles and the Study File before the official start date for Block 12. The study plan indicates where you should be at the end of the first week, should you divide your study time equally between the two weeks. In addition to the text and the articles, there is just one other component — a television programme about the search for extraterrestrial intelligence.

Have a look at the study plan, flick through the printed materials to get a feel for the material you will be studying, and then start at Section 1.

5.1 DS

SUP 83617 3

12 Life in the Universe

All study times are in hours*

Week	Sections of Block 12	Total study time	DVD-multimedia, DVD-video and practical activities
1	1 Introduction	$\frac{1}{4}$	
1	2 The origin of life on Earth	5	
1, 2	3 Life elsewhere in the Solar System	$6\frac{1}{2}$	
2	4 Life beyond the Solar System	5	
2	5 Summary of Block 12		
2	6 Science discovered	$\frac{1}{4}$	
	'Making contact' should be viewed when you have completed Section 4.		

* Section 5 is very short and so a time has not been given for this section.

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S103 discovering science

Life in the Universe

Study File for Block 12

Contents

5.1 DS/P

SUP 836147

1 Introduction

Some scientific questions are of immediate and widespread interest, and they stir our imaginations. Two of these are the focus of this block:

- How did life begin on Earth?
- Is there life elsewhere in the Universe?

These questions have surely been pondered ever since humanity acquired the capacity to wonder, but it is only in the last 100 years or so that we have made significant scientific progress towards answering them, and only in recent decades have huge strides been made. Today, these two questions are the focus of intense scientific activity and exciting progress. This is a fast-moving area, where much is still uncertain; it is beyond reasonable doubt that significant developments will be made before we are many years into the new millennium.

The block is divided into three main sections. In Section 2 we explore the origin and early evolution of life on Earth. This is not only of interest in itself, but also guides our search for life beyond the Earth, because the better we understand how life got going here, and the more we know about its basic requirements, the more surely we shall be able to target our search for life elsewhere. In Section 3 we search the rest of the Solar System, to see whether any of the other planets or their satellites have life on them today, and if not, whether they have supported life in the past. In Section 4 we look beyond the Solar System, at the evidence for planets around other stars, and at how we might discover life on these extrasolar planets.

In each of Sections 2–4 you will need to read several articles, or extracts from articles. These have been drawn mainly from the popular scientific press. They were not written specifically for S103, and although we have taken care to select articles that by and large should be understandable by S103 students, they have not been edited in any way, except that in some cases we are using an extract from a much longer article. You have had only limited opportunities within S103 to study scientific texts not written specially for you. It is an important skill to be able to extract knowledge and understanding from such texts, and Box 1.1, *Getting the most out of scientific articles*, gives you some additional advice about how to do this.

Box 1.1 Getting the most out of scientific articles

We have given advice about reading scientific articles in earlier blocks, particularly Block 8, Activity 6.2, and we have recommended that you read Chapter 2 of the *Sciences Good Study Guide (SGSG)*, which gives general advice about reading and note-taking. Here we want to highlight advice of particular relevance to problems that you might encounter in studying articles not written specially for S103. These might have one or more of the following problematical features.

- There is a lack of action required of the reader — no questions or activities — so it is easy to relapse into a rather passive manner of reading.
- Assumptions about previous knowledge are high, or low, and vary from one part of the text to another.
- There are gaps in the story or in the information given.
- Some parts are very dense, and fine but important distinctions are glossed over.
- The links between text and figures or tables is weak, with perhaps no references in the text to the figures and tables.

This might all sound pretty desperate! It isn't that such articles are badly written. It's just that in many cases they are written with a different purpose in mind from a careful, systematic development of detailed knowledge and understanding. After all, you probably wouldn't want questions in a novel (though sometimes maps and diagrams, and a list of characters with their relationships would be a distinct improvement). The best articles can convey the excitement of the subject with an added buzz and authority if the author is involved in frontier research. You can also get a general awareness of the topic and its context, and with care you will get knowledge and understanding too.

It would be patronizing to give you a 'recipe' for reading the articles in this block, so the following are just suggestions for how you might get the most out

of an article. You have had the opportunity to read articles earlier in the course, notably in Blocks 4, 8 (and 11 if you studied this block), so these suggestions are really a reminder of the good practice that you might already have been following (and not only in relation to articles, but also in relation to all course materials).

Some suggestions for reading articles

In this block, each reading of an article is followed by questions based on the article, and you should look at these *before* you read the article so that you can see more specifically what you are supposed to get out of the reading.

As with most scientific texts you will need to read each article more than once. On a first reading, aim to get a quick overview of the scope and style of the article. Don't get held up by any passages that you don't understand, and avoid the temptation to look up every unfamiliar word in a dictionary. It is however, a good idea to mark any problem passages or words for special attention in a second reading.

On a second reading, highlight what you believe to be key words and phrases. You can now look up unfamiliar words if they seem to be important, but be aware that a dictionary definition might not throw much light on the meaning of scientific terms. You can also use the *Course Glossary* to remind yourself of the meaning of terms that have been introduced earlier in the course. Box 6.3 in Block 1 gives further advice on handling unfamiliar terminology.

At a second or third reading you might try to summarize in a few words what seems to be the key point of each paragraph, perhaps adding some thoughts of your own — such notes can help you with passages on which you are stuck.

Don't allow yourself to get stuck for too long. If there is a difficult passage, you might find that reading the rest of the article two or three times brings enlightenment. Also, your notes on earlier and later passages might help, as might discussing the passage with someone, or looking up some other text (including S103!). If all this fails, then you will have to accept that this particular passage is beyond your reach within the time or effort that you can allow. In many cases this will not prevent you from getting most of what you need from the article for the purposes of Block 12.

Finally, after you have finished with an article it is always worth trying to summarize its content in a few sentences.

The scientific articles clearly give you the opportunity to develop further the skill of active reading. You will also develop your writing skills by preparing short pieces of prose, and by planning and writing longer ones that:

- build an argument, using information from several sources, and with a specific audience in mind;
- critically review the content or presentation of a piece of writing;
- express your own views about an issue.

As well as developing *skills*, this block also revises many scientific *concepts* from earlier blocks. You will consequently encounter a large number of technical terms that you have met before, and *it is therefore particularly important that you have the* Course Glossary *to hand*. Some of the references may be to a block that you chose to omit from your study of the second half of the course. *Do not worry about this*. You should still be able to understand the articles on which Block 12 is based, with the help of the Study File and the Course Glossary. The end-of-course assessment will also have sufficient flexibility to take account of the study choices you may have made.

Activity 1.1 Addressing the big questions

At the beginning of this section two questions were posed. For the first of these, 'How did life begin on Earth?', list a few subsidiary questions that would help you to construct a hypothesis. Each question need only be a few words. Do not spend more than about 5 minutes on this activity, and do not worry if your list is very short!

Note that in this block, each activity is fully specified where it occurs: there are no separate notes on activities as there were in earlier blocks. As with other blocks, comments on the activities are at the end of this Study File.

2 The origin of life on Earth

Earth is the only planet in the Solar System where we know that there is life, and abundant life at that, and so it is a good idea to start our investigation of life in the Universe by considering the origin of life on Earth.

- Recall from Block 3 how the Earth itself originated.
- The Earth itself originated around 4 600 Ma ago, from the disc of gas and dust encircling the young Sun (Block 3, Section 5).

At that time the surface must have been very hot — far too hot to support life. So how did life evolve from non-living matter, or, alternatively, how did life arrive here?

2.1 The nature of the problem

Taking a strictly scientific approach and, therefore, leaving aside the question of divine intervention, we can approach this problem via three interlinked questions:

1. *When* did life first appear on Earth?
2. *What were conditions like* when life first appeared?
3. *How* did life appear?

There are no definitely 'right' answers to any of these questions, only hypotheses that are constantly refined, altered and furiously argued about. Before we enter this debate it is useful to review what is meant by 'life' and the probable nature of the first life (Section 2.1.1), and to consider the essential requirements for life (Section 2.1.2). Sections 2.2–2.4 then consider in turn each of questions 1 to 3.

2.1.1 First life: the universal ancestor

One of the points emphasized in Block 4 (and Block 9 if you studied this block), was the remarkable *uniformity* that exists at the cellular level between organisms. This uniformity suggests strongly that all life that survives on Earth today evolved from a single ancestral stock — the **universal common ancestor**.

Table 2.1 Some examples of characteristics of living organisms. Some are universal and others occur only in certain types of organism.

Example	Characteristic
1	carry out oxidative phosphorylation *a*
2	have a genetic code that can be replicated and that utilizes four nucleotides
3	are composed of one or more cells that are each surrounded by a membrane
4	are composed of cells that can grow and reproduce
5	have chloroplasts *b* and carry out photosynthesis
6	can transform and use an external source of energy
7	are composed of cells that contain mitochondria *c*
8	are composed of cells that have a cell wall (external to the cell membrane)

a Oxidative phosphorylation is the sequence of reactions in cell respiration when oxygen is used and the 'energy currency' molecule, ATP, is produced (Block 9, Section 5.5).

b Chloroplasts are structures (organelles) within plant cells that contain the green pigment, chlorophyll; photosynthesis is the process in which chloroplasts trap light energy and use it to make sugars from carbon dioxide and water.

c Mitochondria are organelles within nearly all eukaryote cells where aerobic cell respiration occurs.

- From the list of characteristics in Table 2.1, choose four that are common to all living organisms.
- The four characteristics are 2, 3, 4 and 6, so these must have been present in the universal common ancestor.

(You may be unable to answer if you did not study Block 9 – but don't worry!)

None of the other characteristics is truly universal. In particular, (1) there are many bacteria that respire anaerobically and do not carry out oxidative phosphorylation (Block 9, Section 5.5); (8) animal cells and certain bacteria do not have a cell wall external to the cell membrane (Block 9, Section 2.1); (7) only eukaryotes (not prokaryotes) have mitochondria (Block 9, Section 2.1); and (5) only **autotrophic** eukaryotes (plants and algae) contain chloroplasts. (See, also, Block 4, Sections 3.1, 3.2 and 4.3.)

We can go further than this in defining the nature of the universal common ancestor. For example, it is reasonable to assume that our earliest ancestors had the simplest possible type of cellular organization.

- So would this early life have been unicellular or multicellular, a prokaryote or a eukaryote?
- Unicellular, because this is the simpler type, and a prokaryote.

Eukaryotic cells acquired organelles such as mitochondria and chloroplasts (the organelles in which photosynthesis takes place in plants, Block 4, Section 2.3) by taking on board prokaryotic partners (the endosymbiotic hypothesis, Block 9, Section 2.3) — so they must be regarded as more complex or advanced. (According to the endosymbiotic hypothesis, early (anaerobic) eukaryote cells engulfed aerobic bacteria, which subsequently became integrated into the 'host' cells to form mitochondria. Similarly, heterotophic eukaryotic cells engulfed and integrated cyanobacteria, which evolved into chloroplasts.)

What emerges from this discussion is that the nearest modern equivalents to the universal common ancestor are bacteria — unicellular prokaryotes. The first cells must have had a surrounding membrane that cut them off from the external medium and allowed some control over what went into and out of the cell. They were able to transform and use energy to grow and reproduce — but the nature of the energy source is still uncertain. And they encoded information that allowed them to make proteins by means of a universal genetic code contained in self-replicating nucleic acid (still used in all organisms). Whether the nucleic acid was ribonucleic acid (RNA) or deoxyribonucleic acid (DNA), however, is another open question.

2.1.2 Essential requirements for life

Perhaps the most important requirement of living organisms is for a liquid solvent in which molecules can dissolve. On Earth the only solvent for life is *water*, which is also involved in many chemical reactions essential to sustain life. So whenever and wherever life appeared on Earth, conditions of temperature and pressure had to be such that liquid water could exist. We cannot be certain that life elsewhere might not use other solvents — liquid ammonia for example — but the consensus is that this is unlikely. Water is probably the universal solvent for life.

Two other requirements for life are:

- appropriate sources of energy
- supplies of the chemicals (atoms, ions or molecules) needed to construct living cells.

- In earlier blocks, what two types of energy used by living organisms were described?
- Light (a small part of the electromagnetic spectrum) which is used by plants in photosynthesis (Block 2, Section 8.4.1, Block 9, Section 6); and chemical energy, for example that stored in the organic molecules of food and released during respiration (Block 2, Section 8.4.1, Block 9, Section 5).

In other parts of the Universe, however, forms of life might have evolved that used other energy sources (other types of electromagnetic radiation, for example): it is at least a possibility. We discuss sources of energy further in Section 2.4.

There could be even more variation in the essential *chemicals* required for life. Only a small number of elements are used by organisms on Earth — between 16 and 20 (the number varies for different organisms), and, of these, only nine are required in relatively large amounts for all species. The three elements that are required in the largest amounts are hydrogen, carbon and oxygen, in that order.

In carbohydrates the ratio of numbers of atoms is about 2 hydrogen : 1 carbon : 1 oxygen (recall glucose, $C_6H_{12}O_6$), whereas in fats there is little oxygen, and carbon and hydrogen occur in a roughly 1 : 2 ratio. The core element, however, is carbon and cell chemistry is based largely on carbon compounds. Carbon is a remarkably versatile element and by far the most likely basis for life outside Earth. But there has been serious discussion about the possibility of life based on silicon, and this cannot be ruled out.

- Why do you think silicon has been suggested as an alternative to carbon as a basis for life? (*Hint*: Think about the chemical properties of these two elements.)

- Silicon lies below carbon in Group IV of the Periodic Table, so the two elements will have many similar chemical properties.

2.2 Timing: when did life appear?

If we know *when* life first appeared on Earth, then we can relate this to the environmental conditions at that time and develop hypotheses about *how* life might have appeared. To give you some appreciation of time-scales, Figure 2.1 shows a scale of the Earth's lifespan from its origin to the present, with a few significant dates

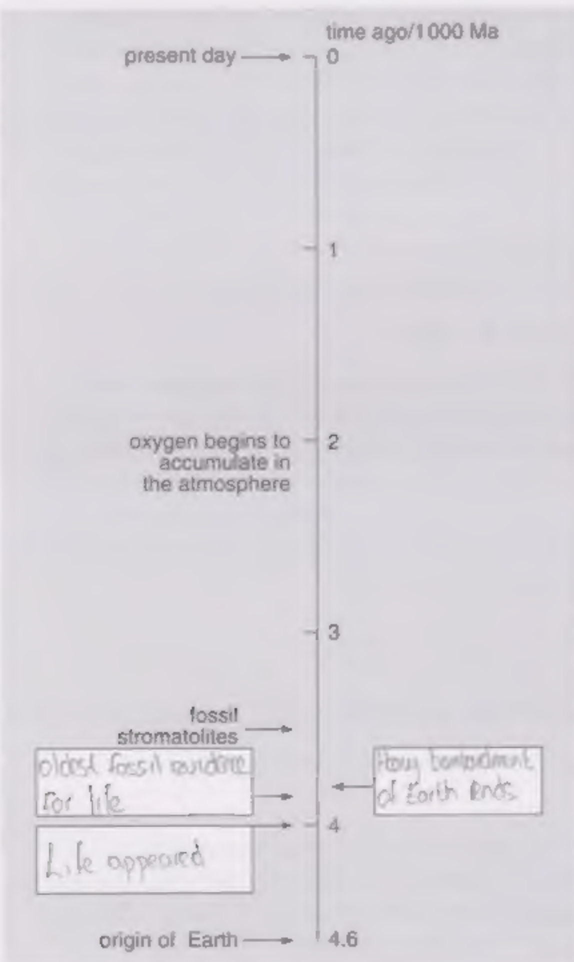


Figure 2.1 Time-scale from the origin of the Earth to the present. As you read the text, add labels to the unlabelled arrows.

marked. The consensus view among scientists, i.e. most but not all agree, is that life appeared on Earth around 4 000 Ma ago: mark this on Figure 2.1 but preferably in pencil so that alterations can be made! If you studied Block 10 you may recall that the dates in Figure 2.1 were discussed in this block, particularly in Sections 2 and 10.

1

This icon indicates that the activity requires you to read Article 1. The articles for Block 12 are printed in three booklets, one black and white, the other two colour.

Articles for Block 12: Part 1 **contains Articles 1, 2, 3, 4, 6, 8 and 9.**

Articles for Block 12: Part 2 **contains Articles 5, 7 and 10.**

Supplementry Articles for Block 12 **contains Supplementary Articles 1, 2 and 3.**

Activity 2.1 The age of life on Earth

(*You should spend no more than about 20 minutes on this activity.*)

Introduction

Article 1 describes the evidence that life existed on Earth around 4 000 Ma ago. It is an extract from a chapter called 'Theories of life's origins' in the book *The Origin of Life* by Carl R. Woese, published in 1984. Carl Woese is (and was when he wrote this book) a professor in the Microbiology Department at the University of Illinois, USA. For many years he has had a special interest in the origin of life, and has studied particularly the most primitive organisms, hoping to find among them clues about life's origin. In 1977 Woese and George Fox, a biologist with similar interests, proposed that there were not two types of life — prokaryotes and eukaryotes — but *three*. The third, new group was the Archaebacteria (now called the Archaea, pronounced 'ar-key-ah'), which is described in the article and which you read about briefly in Block 4, Section 4.3.

Although the book was published some time ago, the first part of the extract, 'The age of life on Earth', is still a good review of current knowledge. However, some updating (and a bit more explanation) is required for the last topic discussed (carbon isotope ratios). This updating and some that is required for the second part of the extract, 'Genetic evidence', will be provided in the text of this Study File after you have read the article. All the technical terms in the article are either defined there or have been defined in earlier blocks of this course and can be looked up in the *Course Glossary*.

Answers to questions in activities are with the Comments on activities.

After reading the article you will be asked to answer Questions 2.1.1–2.1.4 below. Have a quick look at these questions now so that you can make notes, mental or written, that will help you to answer the questions.

You should now read Article 1.

Question 2.1.1 What two kinds of fossil evidence suggest that life existed at least 3 500 Ma ago? ◀

Question 2.1.2 What kind of geological evidence suggests that life existed 3 800 Ma ago? ◀

Question 2.1.3 What sorts of genetic data were used to construct the universal genealogical tree ('tree of life')? ◀

Question 2.1.4 How does the genealogical tree in Figure 21 of Article 1 help to date the timing of the origin of life? ◀

Updating Article 1: isotope ratios

More work has been done on isotope ratios, notably on the ratio of the two stable isotopes of carbon, ^{12}C and ^{13}C. Ratios of stable (i.e. non-radioactive) isotopes can be used to obtain important information. When carbon dioxide is *fixed* in photosynthesis, a lower proportion of the heavier ^{13}C isotope is incorporated into organic matter than of the lighter ^{12}C isotope. So organic sediments derived from photosynthetic organisms are relatively depleted in ^{13}C compared with inorganic carbonates.

In 1988 the German scientist Manfred Schidlowski published data which summarized more than 10 000 measurements of $^{13}C/^{12}C$ values in marine organic sediments ranging in age from the present to 3 500 Ma. Figure 2.2a (*overleaf*) summarizes his data, expressed in terms of the difference in the $^{13}C/^{12}C$ value relative to a particular inorganic carbonate source. Thus:

$$\text{relative difference in } {}^{13}C/{}^{12}C = \frac{\left({}^{13}C/{}^{12}C\right)_{org} - \left({}^{13}C/{}^{12}C\right)_{inorg}}{\left({}^{13}C/{}^{12}C\right)_{inorg}} \qquad (2.1)$$

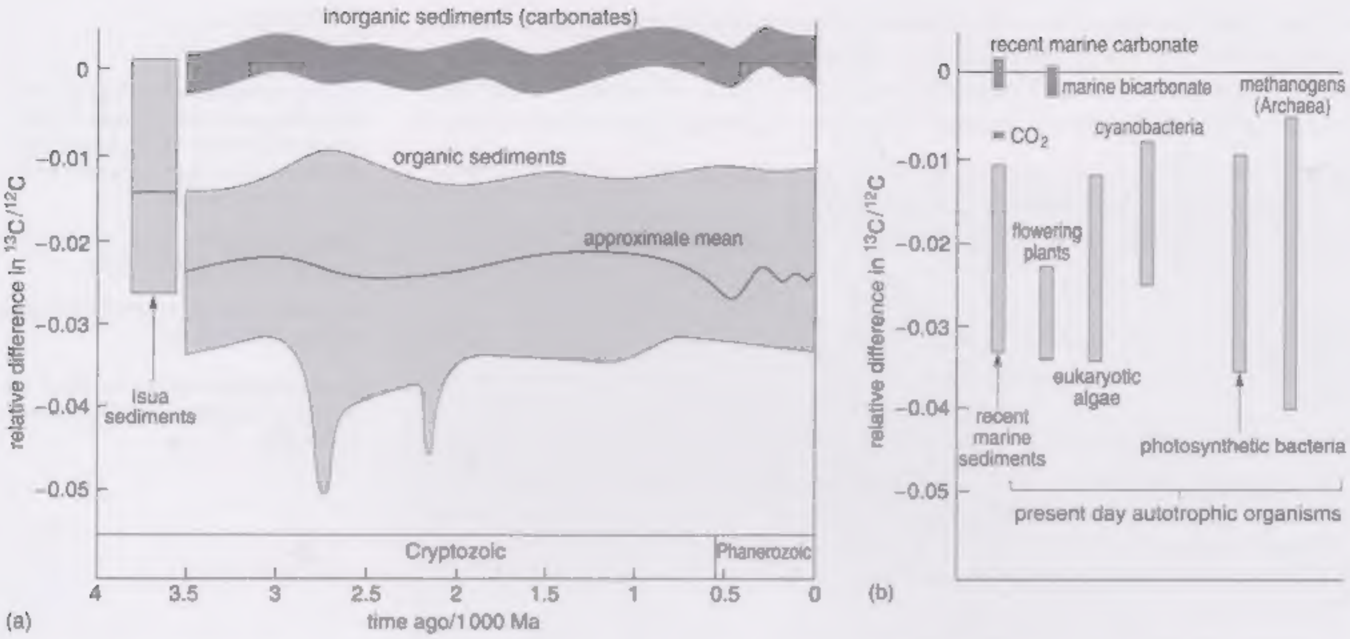


Figure 2.2 (a) Relative differences in $^{13}C/^{12}C$ in organic carbon sediments (pale grey) and inorganic carbonate sediments (darker grey) over 3 800 Ma of the Earth's history. The widths of the grey bands indicate the ranges of the measured values, and the line within the light grey bands is the mean value. (b) Relative differences in $^{13}C/^{12}C$ in various types of living autotrophs that fix CO_2 and in recent marine organic and inorganic sediments.

Notice that the values for organic sediments in Figure 2.2a are negative, indicating a *depletion* of ^{13}C in the organic sediments compared to the inorganic sediments; the greater the depletion, the more negative the value.

Clearly there is a problem with the results shown in Figure 2.2a for sediments from Isua in Greenland, which were discussed in Article 1. Their ^{13}C depletion is not as great as that of later organic sediments but they are still depleted in ^{13}C compared to inorganic sediments. How can this discrepancy be explained, and do these ancient Greenland sediments really provide evidence of photosynthetic organisms living 3 800 Ma ago? Consider the three possible explanations below in conjunction with:

- the data in Figure 2.2b — this figure shows the relative difference in the $^{13}C/^{12}C$ value in various types of *living* autotrophs that fix CO_2.
- the fact that when sediments undergo metamorphism (as the result of heating and compression (Block 3, Section 9.4 and Block 10, Section 7) this tends to release CO_2, with relatively more $^{12}CO_2$ being driven off than the heavier $^{13}CO_2$, so the sediments become enriched in ^{13}C.

Explanation 1 The Isua sediments were derived from different types of autotrophs than the later sediments.

Explanation 2 The Isua sediments were derived from similar autotrophs to the later sediments but metamorphism has changed their ratio of ^{13}C to ^{12}C.

Explanation 3 The Isua sediments are not organic in origin but inorganic, and their ratio of ^{13}C to ^{12}C has been changed through metamorphism.

Explanation 2 was offered by Schidlowski. He argued that metamorphism would have tended to drive off preferentially $^{12}CO_2$ (as we described above) and hence would have reduced ^{13}C depletion, giving a less negative value. The dark grey band at the top of Figure 2.2a means that Explanation 3 cannot be correct because, if Isua sediments were inorganic, then driving off $^{12}CO_2$ would have given a positive and not a negative value. Explanation 1 cannot be ruled out because you can see from Figure 2.2b that some autotrophs, notably some types of photosynthetic bacteria, cyanobacteria and the methanogens (a group of Archaea that generate methane gas), do have, and therefore produce sediments that have, values for ^{13}C depletion that are comparable to those of the Isua sediments. However, it is rather unlikely that the whole community of autotrophs suddenly changed after 3 800 Ma, so Explanation 1 is not regarded as very likely.

If we accept Explanation 2, this means that the *original* isotope ratio of the Isua sediments (before metamorphism) would have been the same as in later organic sediments, which would mean that CO_2 fixation was, indeed, going on 3 800 Ma ago.

Not all scientists agreed with this conclusion, arguing, for example, that there was too little organic carbon in the Isua rocks to obtain a clear isotope ratio, and the values obtained are quite close to some that are found in inorganic sediments. In 1996, however, a group of scientists from California, Australia and the UK provided stronger evidence of life not only at 3 800 Ma but also at 3 850 Ma — 50 million years earlier! Instead of analysing *all* the organic carbon in ancient rocks (whole rock analysis), much of it severely altered during rock metamorphosis, they used a scanning instrument (known as an ion microprobe) to analyse tiny particles of organic carbon associated with apatite, a calcium phosphate mineral. In some unknown way, this association seems to have protected the organic carbon from having its carbon isotope ratio altered during metamorphosis. They measured carbon isotope ratios in the Isua sediments, and in the Earth's oldest known sediments, from Akilia Island in west Greenland. Table 2.2 shows a summary of these new data. Also included are data from somewhat younger sediments, from Pilbara in Western Australia.

Table 2.2 Relative differences in the $^{13}C/^{12}C$ values in sedimentary rocks of three ages. Apatite-protected samples were analysed with an ion microprobe. Whole-rock analyses were carried out in earlier studies on samples that included unprotected and protected material. The ± value given for each value is an indication of the uncertainty of the data, and consequently their reliability.

Sample		Difference in $^{13}C/^{12}C$	Number of samples analysed	Range of values
Pilbara sediments (3 250 Ma)*	apatite-protected	−0.026 ± 0.003	11	−0.019 to −0.034
	whole-rock	−0.030 ± 0.004	>10	
Isua sediments (3 800 Ma)	apatite-protected	−0.030 ± 0.003	7	−0.024 to −0.036
	whole-rock**	−0.010 ± 0.005	>10	
		−0.012 ± 0.004	>10	
Akilia sediments (3 850 Ma)	apatite-protected	−0.037 ± 0.003	18	−0.021 to −0.049

*These sediments are known with certainty to derive from living organisms.
**These values relate to two sets of measurements by different groups of researchers.

- How do the data for apatite-protected carbon in the Isua sediments strengthen the case for Explanation 2 described above?

- For the apatite-protected material, ^{13}C depletion is greater, which is consistent with the hypothesis that depletion is reduced when the carbon is not protected.

The data for Pilbara sediments show that association with apatite does not in itself change $^{13}C/^{12}C$ values (e.g. increase ^{13}C depletion), because there is no significant difference here between whole-rock and apatite-protected samples — in contrast to the strongly metamorphosed Isua sediments. This further supports Explanation 2.

- What conclusions do you draw from the data in Table 2.2 and Figure 2.2b about the nature and origin of carbon in the Akilia samples?

- ^{13}C depletion is particularly high in these samples (there is a large *negative* value for the relative difference in the $^{13}C/^{12}C$ value), which certainly suggests that the carbon derives from organisms that fixed CO_2.

But why is the value so high and why is there such a large range of values (last column in Table 2.2)? At present there are no answers to these questions, but you can see from Figure 2.2b that some living autotrophs, notably certain photosynthetic bacteria and methanogens, do have similar depletions. So perhaps there really were different communities of autotrophs present at this very early date, in other words, there could be some truth in Explanation 1!

This last suggestion is not too outrageous. If we accept that the Akilia data are reliable (and everything indicates that they are), and that no known *non*-biological process could have produced such strong depletion of ^{13}C, then we have to conclude that organisms able to fix CO_2 existed 3 850 Ma ago. The most extreme value for Akilian ^{13}C depletion (–0.049) could not have been produced by any known photosynthetic organisms (i.e. those which use light to fix CO_2) but it could have been produced by organisms like the methanogens which are **chemo-autotrophs** and fix carbon dioxide using not light energy but energy released by the oxidation of simple compounds such as hydrogen sulfide (H_2S). Chemo-autotrophs can, of course, function in the dark; you will read later in this section that they are among the favoured candidates for the earliest forms of life on Earth. So although we cannot be absolutely certain, it seems more and more likely that autotrophic life of some kind was present on Earth 3 800–3 850 Ma ago — but exactly what kind is still a mystery.

Updating Article 1: genetic evidence

The genetic evidence described in the second part of the extract also requires some updating. More work has been done to sequence and compare not only RNA molecules but also DNA from different kinds of organisms. By 1996 complete genome sequences had been obtained for members of each of the three main branches shown in Figure 21 in Article 1. These newer sequence data have confirmed what many scientists still doubted: that there are indeed three branches, now known as *domains*, on the universal phylogenetic tree; their names have changed slightly to Bacteria, Archaea and Eukarya (which were mentioned in Block 4, Section 4.3).

A more recent version of the universal phylogenetic tree is shown in Figure 2.3. Remember that the branching is shown in the sequence of times at which it occurred, and that the more recently the branches diverged, the more closely related are the organisms.

- Comparing Figure 2.3 with Figure 21 in Article 1, what is different about the relationship between the Archaea (Archaebacteria) and the Eukarya (Urkaryotes/Eukaryotes)?

- It is closer in Figure 2.3, in that the Eukarya branch off the Archaea in this figure. The more recent genetic evidence indicates that Archaea are more closely related to Eukarya than to Bacteria (previously called Eubacteria).

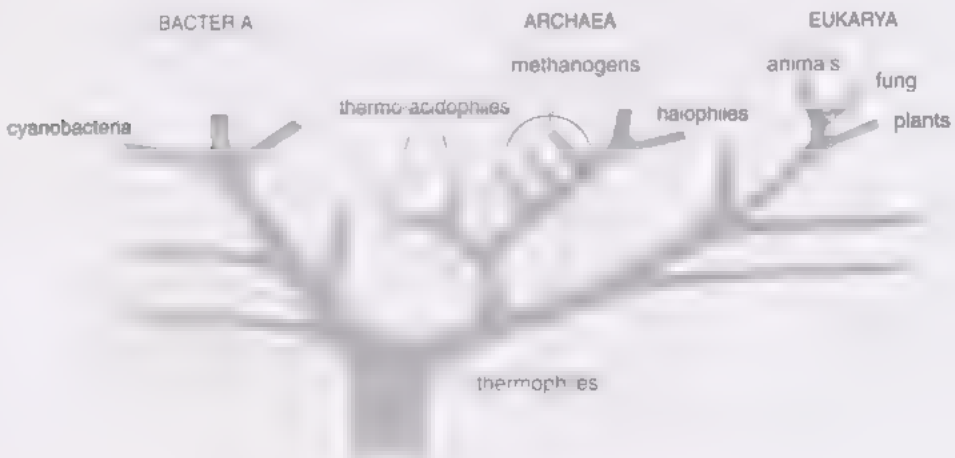


Figure 2.3 A more recent version of the universal phylogenetic tree showing the three domains (branches) of life: all branches shown have living representatives (unlike some trees which you met in earlier blocks). Halophiles live in very salty environments such as the Dead Sea. Methanogens release methane. Thermo-acidophiles live in very hot and very acid places. For clarity, some branches have been left unlabelled.

Notice also in Figure 2.3 that several of the branches near the common trunk of the tree (and, therefore, regarded as being of most ancient origin and closest to the universal common ancestor) are ringed to indicate that the organisms live at very high temperatures. These extreme thermophiles (from *thermos*, 'heat' and *phylos*, 'loving') typically live at temperatures of 80–100 °C or more in places such as hot springs around volcanoes and hydrothermal vents, the latter being sites on the deep ocean bed where very hot water gushes out (Block 3, Section 14.1.2). Later you will see that life might have originated in such very hot places, a hypothesis that matches nicely this finding that living organisms of the most ancient origin are thermophiles.

2.3 Earth's early environment

If one accepts the majority view that life appeared on Earth around 4 000 Ma ago, then, in order to develop hypotheses about how this might have happened, we need to know what conditions were like then, and earlier. What was the temperature and the composition of the atmosphere and of the oceans?

The Earth itself provides virtually no clues because no rocks or other kinds of geological evidence remain from before about 4 000 Ma ago (Block 3, Section 16; Block 10, Section 8). Instead, we must turn to astrophysicists and planetary scientists for information about the Moon and other planets, and for information about other stars to compare with our Sun. Based on such information, we describe in Sections 2.3.1–2.3.3 factors that are generally believed to have had major influences on the Earth's early environment.

2.3.1 Bombardment from space

From its origin until about 3 800 Ma ago, the Earth was subjected to a heavy bombardment by bodies from space left over from the formation of planets, such as:

- comets, which are largely icy in composition, and up to a few kilometres across;
- rocky bodies, which have a continuous size distribution, ranging from a few of lunar size, to larger numbers of bodies several kilometres across called planetesimals, to even larger numbers of metre-sized bodies called meteoroids (or meteorites if they survive to reach the Earth's surface), to huge numbers of dust particles;
- other planetesimals, that have a mixed icy–rocky composition.

Much of the evidence for a heavy bombardment comes from observations of impact craters on the Moon and on certain other planets in the Solar System. You can read about this evidence later, in Article 2, which also makes suggestions about possible effects of the bombardment on the Earth.

The point we make here is that the early Earth would have been a very unstable place, particularly before about 4 200 Ma ago, with large impacts generating a great deal of heat (enough to boil off whole oceans according to some scientists) and throwing up huge clouds of dust and steam. It is difficult to see how life could have originated in such conditions. Furthermore, the lunar evidence suggests that, though the heavy bombardment gradually declined, there might have been an increase towards its end — a *late heavy bombardment* — ending about 3 800 Ma ago. You might like to mark this event on Figure 2.1, and also the date of the oldest fossil evidence for life — 3 850 Ma ago

How does this information match the evidence in Section 2.2 about the timing of the origin of life on Earth?

The suggestion in Section 2.2 was that life originated around 4 000 Ma ago, which would have been before the end of the late heavy bombardment.

Even without a late surge, the bombardment 4 000 Ma ago would still have been heavy. Somehow this earliest life must either have been protected from the effects of

bombardment, or else it became extinct and life originated a second time later on. Indeed, there could have been several origins and extinctions.

Another possibility, although it seems rather unlikely, is that life originated when the heavy bombardment was in steep decline 3 900–3 800 Ma ago, and then evolved very rapidly so that autotrophs were present within about 50 Ma. Living organisms might even have arrived with the late heavy bombardment, an idea explored in Section 2.4!

2.3.2 The early atmosphere and oceans

How did the Earth's early atmosphere form and what was it like? Based on comparisons with neighbouring planets such as Mars and Venus, it seems most likely that the atmosphere formed partly through the release of gases trapped within the Earth. Volcanoes belched out gases, including water vapour, which were retained as an atmosphere by the gravitational attraction of the Earth. Such *outgassing* of a similar mixture of gases still goes on today — recall Block 3, Section 8.1 and the video on volcanoes (Activity 8.1). An additional source of gases, especially water vapour, was the comets and planetesimals that impacted the Earth during the heavy bombardment.

- (a) As well as water vapour, what gas(es) would you expect to have been present in substantial quantities in Earth's early atmosphere? (b) Which gas (that is present today) would have been absent?

- (a) The gas mentioned in Block 3, Sections 5 and 18, as being abundant in the present atmospheres of Mars and Venus (Earth's nearest neighbours), and released during volcanic eruptions on Earth, is carbon dioxide (CO_2). Nitrogen gas (N_2) is the next most abundant gas in the atmospheres of Mars and Venus and (although you were not told this) it is also a component of volcanic gases.
(b) Oxygen (O_2) would have been absent.

Oxygen is absent from volcanic gases, and is present at only very low levels in the atmospheres of other planets.

- When did significant levels of oxygen begin to accumulate in the Earth's atmosphere?

- 2000 to 2500 Ma ago (see Figure 2.1).

So an early atmosphere consisting mainly of CO_2 and N_2 and devoid of oxygen is the most likely scenario for the early Earth. There would probably also have been small quantities of other volcanic gases, including sulfur dioxide (SO_2), ammonia (NH_3) and methane (CH_4), and water vapour would certainly have been present. Because oxygen was absent there would have been no layer of ozone (O_3) in the upper atmosphere of the early Earth (Block 3, Section 18.2).

- What effect would this have had on the type of solar radiation reaching the Earth's surface?

- It would have contained far more short-wavelength radiation (ultraviolet, UV). Radiation with these wavelengths is either completely or largely absorbed by the ozone layer.

Remember (Block 3, Section 18.2, and Block 10, Section 2.3) that the shorter-wavelength UV radiation is potentially very damaging to living organisms. This is one of many reasons why the surface of the early Earth would have been extremely inhospitable to life.

What about the early *oceans*? For a start, we cannot be certain when oceans actually formed. Initially, conditions were probably too hot and the bombardment from space was too intense for oceans to condense. Thus, Woese (the author of Article 1) has argued that most of Earth's water was present as steam! But the ancient Isua rocks from Greenland mentioned earlier indicate that by 3 800–3 850 Ma ago oceans were present. These rocks have a structure that suggests that they were formed partly from

sediments deposited in water and partly from lava flows that cooled under water. So a reasonable assumption (and that is all it is) is that oceans had formed by 4 200–4 000 Ma ago.

The chemical composition of early oceans is again a matter of guesswork. Modern seawater is salty, i.e. it contains quite large amounts of dissolved ions.

- Where do you think the ions in seawater come from?
- One answer is from rocks: ions in rocks under the sea may pass into solution, and ions from rocks on land can enter rivers that carry them into the oceans. Another answer is from the atmosphere: carbon dioxide, sulfur dioxide and hydrogen chloride dissolve in rain and form hydrogen carbonate, sulfate and chloride ions respectively. If you read Block 10 you may recall that this topic was discussed in Block 10 (Sections 6.3.2 and 10.2).

One metallic ion which is common in rock minerals, iron, was probably much more abundant in the early ocean than it is today — perhaps 1 000 times more so. Iron has two principal ionic forms, iron(II) (Fe^{2+}, ferrous) and iron(III) (Fe^{3+}, ferric). Iron(II) is readily converted to iron(III) under oxidizing conditions; in addition, iron(II) compounds are generally soluble in water whereas relatively few iron(III) compounds have this property. You will be familiar with these properties of iron if you did the optional practical work in Block 6 (Activity 13.2).

- So which form of iron would have been present in the early oceans, and why was it more abundant than it is today?
- Iron(II) (the reduced form of iron) would have been present, because any iron(III) that formed would have precipitated out as insoluble compounds. Iron(II) was more abundant than it is today because there was no oxygen or other oxidizing agent to convert it to iron(III) (see Figure 2.1).

The present-day oceans contain relatively little iron because iron(III) can now readily form and be precipitated. The appearance of oxygen in the Earth's atmosphere about 2 000 Ma ago led to the first formation of abundant quantities of iron(III) (Figure 2.1).

Volcanic eruptions under the sea were probably more frequent on the early Earth than today, and were another factor influencing the chemical composition of the oceans. Of particular significance (as you will see later) were hydrothermal vents, similar to those described in Block 3, Section 14.1.2, where hot water gushes out, saturated with minerals and with gases such as methane and carbon dioxide (as shown in the DVD-multimedia activity 'Exploring the Mid-Atlantic Ridge', Block 3, Activity 12.1).

The picture of the early oceans emerging from this discussion is of a fairly salty environment with very high levels of reduced iron, iron(II), and local chemical hot spots associated with volcanoes and hydrothermal vents. Additionally, the heavy bombardment of Earth from space might have significantly affected the composition of the oceans, as you will see in Article 2.

Activity 2.2 Seeding Earth: comets, oceans and life

(You should spend no more than about 25 minutes on this activity.)

Introduction

Article 2, 'Seeding Earth: comets, oceans and life' by Christopher Chyba, discusses the intensity of the heavy bombardment of Earth (also called the 'early bombardment' in the article) and the evidence that material from comets might have influenced the composition of the early ocean. It was published in a popular science journal, *The Planetary Report*, in 1990. When he wrote the paper the author was a postgraduate student at Cornell University, USA, carrying out research in space sciences. Before that he studied theoretical physics and the history and philosophy of science at Cambridge University, UK; he currently (2002) holds the Carl Sagan Chair for the Study of Life in the

Universe at the SETI Institute, California, and is also an Associate Professor and Co-Director of the Center for International Security and Cooperation (CISAC) at Stanford University, USA. Since 1987 he has published commentaries, papers and reviews in leading scientific journals, but in this article a relatively young scientist presents his ideas to a wider audience.

The first two sections of the article are about the general nature of comets and what happens if a comet collides with a planet. Then, in the section 'Early bombardment', Chyba summarizes the evidence that the early Earth was subject to intense bombardment from space, and he describes in the box on p. 22 of the article how the bombardment was dated. He goes on to estimate the total mass delivered to the Earth in the period between 4 500 and 3 800 Ma ago ('Comet-delivered oceans'); he then discusses the evidence that collisions with comets could have contributed significant quantities of water to the Earth's oceans.

The last two sections are about the possible significance for the origin of life on Earth of organic molecules arriving with comets or meteoroids. The section 'Seeding Earth with organics' anticipates the discussion in Section 2.4 about chemical evolution and the origin of life, so don't worry if you cannot follow all of the arguments.

As you read the article you should assemble information that will enable you to answer Questions 2.2.1–2.2.3, so look briefly at these questions before reading the article.

You should now read Article 2.

Question 2.2.1 How have rocks collected from the Moon provided evidence about the early bombardment of Earth? ◀

Question 2.2.2 Assess the evidence (i.e. say *what* the evidence is and how strong or weak it is) that Earth's early ocean derived a substantial part of its water from comets. ◀

Question 2.2.3 Apart from delivering water to Earth, how might comets have influenced the origin of life? Discuss the uncertainties of the role of comets in life's origin. ◀

The ideas described in Article 2 have not been seriously challenged, and research reported in 1996 suggested that comets might contain organic molecules which could have contributed to the synthesis of nucleic acid-like polymers on the early Earth: such organic molecules were synthesized by irradiating a frozen mixture that roughly simulated conditions in a comet. There is, however, growing evidence that large bodies such as comets might have been less important as sources of organic chemicals for the early Earth than interplanetary dust — minute particles which even today still reach the Earth's surface in considerable quantities, about 10^8 kg y^{-1}.

Note that, contrary to the statement on p. 22 of the article, small quantities of water have very probably now been detected in the lunar polar regions, perhaps the surviving proportion of larger quantities delivered by comets.

2.3.3 Earth's early climate

We mentioned earlier and you read in Article 2 that for the first 800 million years of its life (4 600–3 800 Ma ago) Earth was a turbulent place. The early bombardment would have been particularly heavy 4 600–4 200 Ma ago. But what was the climate like, especially the temperature, over the period 4 200–3 800 Ma, when life is thought to have appeared?

- Think back to Block 2, Section 5. What is the *primary* energy input that determines the Earth's GMST (global mean surface temperature) today?

- Solar electromagnetic radiation absorbed by the surface — this is the radiation intercepted by the Earth (the solar constant times the interception area), less the amount reflected back to space (specified by the planetary albedo).

(There is also radiation emitted by the atmosphere — this determines the size of the greenhouse effect, which depends on the amounts of greenhouse gases in the atmosphere. This radiation is derived from solar radiation.) If our Sun behaves like other, similar stars, then 4 000 Ma ago it would have emitted 20–30% less energy than it does today (Block 2, Section 9). The distance of the Earth from the Sun has not changed significantly, and therefore the solar constant would have been much lower. Under today's conditions, this would mean a GMST well below 0 °C, with all surface water frozen solid. That in turn would give a high surface albedo because ice reflects solar radiation very effectively, so these two factors would have tended to make Earth a very cold place indeed.

However, other factors might have countered this cold scenario. First, the Earth's interior was much hotter than it is today and heat was being released from it at a greater rate; this would have made the ocean floor warmer but probably had little effect on surface temperatures. Second, there were all those impacts from space, which generated a great deal of heat. Third, and potentially of greatest significance, there was probably a much stronger greenhouse effect than today.

- Why would the greenhouse effect have been stronger?

- Because of the large atmospheric quantities of CO_2, which is a powerful greenhouse gas.

A fourth factor is that cloud cover, which reflects solar radiation back into space, might have been lower than it is today, thus reducing the albedo of the early Earth and acting to increase GMST. Most scientists who have worked on this problem have concluded that the warming and cooling factors roughly balanced out and that the Earth around 4 000 Ma ago had much the same average temperature as today or was somewhat warmer. There are other views, however.

Activity 2.3 Cold start

(You should spend no more than about 20 minutes on this activity.)

Introduction

Article 3 'Cold start', which you will refer to in this activity, was published in a popular journal *The Sciences* in 1995. It suggests that the Earth might have been a very cold place when life began here. The author, Jeffrey L. Bada, is a chemist (see the note at the end of the paper) who has worked jointly with one of the most experienced researchers into the origin of life, Stanley Miller.

The first part of the article describes Miller's early work on chemical evolution (also described briefly in Article 2) and some later ideas about the origin of life which will be discussed in Section 2.4. Then the article discusses conditions on Earth when life appeared and, in the third section, pinpoints a problem: if the early atmosphere consisted largely of carbon dioxide and nitrogen gas, then the chemical reactions necessary to generate amino acids and other building blocks of life would not have happened. Bada looks at two solutions to this problem. The first is that building blocks came from space through the early bombardment (as suggested by Chyba in Article 2). The second is that the Earth was frozen at the surface but had liquid water deep in the oceans where chemical evolution could have taken place.

As you read Article 3, assemble information so that you will be able to answer Questions 2.3.1 and 2.3.2 below.

You should now read Article 3.

Question 2.3.1 What argument does Bada present *against* the hypothesis that organic molecules from space contributed significantly to chemical evolution on the early Earth? What evidence does he give to support his argument against the hypothesis? ◀

Question 2.3.2 What is Bada's alternative hypothesis? What assumptions are made as a basis for this hypothesis and is any evidence given to support these assumptions? ◀

The suggestion that a likely site for the origin of life was around hydrothermal vents has been made many times.

What genetic evidence that is consistent with this idea was presented in Section 2.2?

Many of the micro-organisms (especially Archaea) that have the most ancient origins are extreme thermophiles (heat-lovers), living in very hot conditions. Perhaps, therefore, the universal common ancestor was a thermophile that lived in the hot water around hydrothermal vents.

However, hot places may also occur elsewhere on the Earth — in surface pools close to volcanoes, for example — so thermophily in ancient organisms does not *necessarily* mean that life originated close to hydrothermal vents.

2.4 How did life originate?

The scene is now set. We have some idea of when life appeared on Earth and of conditions at that time, but the question remains, how did it happen? Two general mechanisms have been suggested for the origin of life. The most widely accepted view — mentioned already in Articles 2 and 3 — is that living cells were organized from non-living organic molecules such as lipids (fatty substances), proteins and nucleic acids (Block 4, Section 3.2; Block 8, Section 16.2 and Block 9, Section 3) which had themselves evolved from simpler precursors by a process of **chemical evolution**. An alternative view is that life had an **extraterrestrial origin** and reached Earth from space, carried by comets, meteoroids or dust particles.

Although the majority view still favours chemical evolution, some scientists have an open mind on the question. There is, for example, the problem of the time available for chemical evolution on Earth.

Recall the time at which life probably appeared on Earth. And recall (Section 2.3.3) what conditions were like before this How much time was probably available for chemical evolution?

We suggested earlier that life appeared around 4 000 Ma ago. The Earth originated around 4 600 Ma ago and was too hot for life (lacking, for example, liquid water) and too unstable (because of the heavy bombardment) until at least 4 200 Ma ago (Section 2.3.1). That leaves only about 200 Ma for chemical evolution, which seems a very short time for such an immensely complex process.

For example, it took about 2 000 Ma from the supposed origin of life (4 000 Ma ago) to the appearance of eukaryotic cells with a nucleus (2100 Ma ago); and multicellular animals were not abundant until another 1 500 Ma had elapsed — 610 Ma ago. We have no reason to believe, therefore, that early evolution, chemical or biological, proceeded at a particularly fast rate. The astronomer Sir Fred Hoyle resolutely maintained that an extraterrestrial origin must be the case because it is just too unlikely that chemical evolution could have led to life on Earth in the time available.

An argument against an extraterrestrial origin has been that no living organism could survive the extreme cold and high radiation environment of outer space, nor the trauma of descent through the Earth's atmosphere and the explosive impact at the surface. When a large object travelling very fast enters the Earth's atmosphere, there is friction with the atmosphere that generates a great deal of heat. This is why the return module of a spacecraft has a stout heat shield and why meteoroids streaking through the atmosphere are seen as bright meteors (Block 5, Figure 6.2) — they are glowing hot and heat the atmosphere along their paths! Surely, it is argued, any living cells on the surface of such bodies would be

burnt up during their descent or destroyed in the gigantic explosion when an extraterrestrial body impacted on Earth. Against this argument, three points can be made.

1 The interiors of freshly fallen meteorites are known to be cold — only the surface is heated during passage through the atmosphere. On impact, the typical meteorite might break up, but it is not massive enough to be melted or vaporized. Organisms in the interior could thus survive.
2 Minute particles of dust constantly reach Earth from space. Because they are so small, the temperature rise in the slower-moving ones as they travel through the Earth's atmosphere is much less than it is for larger objects — they are rapidly decelerated and then float downwards. Perhaps some heat-resistant forms of life (such as spores) could be associated with such particles.
3 Single-celled organisms could be ejected from a planet into space as a result of violent explosions — from volcanoes or meteorite impacts, for example. It has been suggested that they could then be propelled through space by the radiation emitted from stars. A group of Canadian scientists proposed (1996) that such radiation-driven life could survive the hostile environment of space for millennia if it were covered by a thin layer of carbon — a sort of protective dust jacket. Frictional heating on re-entry to a planetary atmosphere would then have to be sufficient to fracture this dust jacket (so that the organisms could start functioning again) but not so great as to burn them up completely.

So, although it is still a minority view, serious consideration is being given to the possible extraterrestrial origin of life on Earth. This does allow the possibility of a lot more than 200 Ma or so for life to have originated. However, we shall stick with the majority view and consider some ideas about chemical evolution on Earth leading to the origin of life.

2.4.1 Chemical evolution

Until the 1950s, the first steps in chemical evolution were assumed to have taken place in the atmosphere, which was thought to contain substantial amounts of ammonia, hydrogen and methane. In such an atmosphere, which is strongly reducing, i.e. it tends to promote reduction reactions (Block 8, Section 14.2.2, and Block 9 Section 4.2), UV radiation from the Sun and electrical discharges from lightning can provide the energy necessary to produce a wide array of simple building blocks, such as amino acids (Block 8, Section 16 2, and Block 9, Section 3.3.3). These would then have entered the oceans in rain and accumulated there. Stanley Miller's experiments described in the first section of Article 3 are consistent with this hypothesis (note the terminology!).

Unfortunately for this early hypothesis, the atmosphere was probably *not* strongly reducing, but is more likely to have been predominantly nitrogen and carbon dioxide, as described in Section 2.3.3 and in Article 3, so the hypothesis had to be discarded. Bada describes one alternative hypothesis: that chemical evolution occurred in the deep oceans beneath their frozen surfaces. But there have been many other hypotheses. Woese (author of Article 1) has argued that reactions occurred on the surfaces of particles of pyrite (iron sulfide) blasted into a steamy atmosphere by the early bombardment. Other people have suggested that scums at the ocean surface, shallow pools, or the surface of clay particles in pools provided suitable sites. And reduced iron, iron(II), might have played an important role, reducing CO_2 in the presence of UV radiation and water to formaldehyde, HCHO, which is a useful precursor to several organic molecules, including sugars. Note that water, either as a reactant or as a liquid medium, is essential for all steps in chemical evolution.

There are almost as many hypotheses as there are scientists researching the subject, and you will meet more hypotheses later in Supplementary Article 1 (SA1), 'Life's

Rocky Start'. So let us assume that simple building blocks were formed, and move on to the next problem, which is one of concentration, and the unhelpful chemical reaction known as hydrolysis (Block 8, Box 16.2). For simple building blocks to react further to produce larger molecules, especially polymers, the reactant molecules must be quite concentrated to increase the reaction rate. And if the products are not to break down by reacting with water (the hydrolysis reaction), they must be held in some special environment. The solid surface of rocks or clay particles provides one such environment because not only do such surfaces seem to promote polymerization reactions, they also protect the reaction products. This is why several hypotheses focus on solid surfaces as the site of chemical evolution.

4

Activity 2.4 Nature's feet of clay

[illegible]

Question 2.4.1 [illegible]

Further ideas about the role of solid surfaces are described in SA1, which you can read later.

Suppose, therefore, that reactions on solid surfaces produced a rich mixture of biological polymers (Block 8, Box 16.1); for example: phospholipids (fatty molecules (lipids) linked to phosphate groups, (Block 9, Section 3.6.2), which could spontaneously form a membrane-like structure over the mixture and segregate it more firmly from the surrounding medium); chains of amino acids (peptides) or even proteins (Block 8, Box 16.1); and simple polynucleotides, the forerunners of nucleic acids (Block 4). This is still far from being a living cell but it is the sort of system that could have developed during chemical evolution, regardless of whether that evolution occurred on Earth or on another planet. Let us assume that from such simple beginnings arose the precursors of cells (protocells) from which the first true cells evolved. We shall consider just two important questions about protocells and the first cells: how did they obtain the energy needed to grow and maintain themselves? and how did they replicate — what sort of genetic material did they have?

2.4.2 The energy question

Early theories about the origin of life assumed that the first cells were heterotrophs.

- Recall the definition of a heterotroph (Blocks 4 and 9) and suggest where the first cells obtained energy if they were heterotrophic.

Heterotrophs (e.g. animals) obtain energy by breaking down complex organic molecules. For early heterotrophic cells, such molecules would have had to come from the surrounding medium which, according to early theories, was thought to be a kind of soup rich in organic molecules. The energy released would have enabled the formation of complex organic molecules required for growth and maintenance.

But the scenario we have described, based on more recent ideas, does not have a rich organic soup filling the ocean. Increasingly, the balance of opinion has shifted towards the view that the first cells and their immediate precursors (protocells) were *autotrophic*, i.e. in order to synthesize from small inorganic molecules the large organic molecules that are the basis of life, they obtained energy from light or (and this is an idea you met in Section 2.2) by oxidation of simple inorganic compounds such as iron sulfide or hydrogen sulfide, or of simple one-carbon molecules such as methane (CH_4). Such cells are called chemo-autotrophs and there are bacteria and archaea living today that obtain energy in this way.

How does the idea that the earliest cells were autotrophs match the evidence from carbon isotope ratios about the nature of life in the oldest rocks on Earth (Section 2.2)?

It matches well. The carbon isotope ratios in the rocks from Akilia Island indicate that autotrophs, probably chemo-autotrophs but possibly photo-autotrophs as well, were present.

The light reactions of photosynthesis (i.e. those that involve a photochemical reaction during which the energy of sunlight is trapped, Block 9, Section 6.2) might seem horribly complex. The basic process that traps energy is really quite simple however, all that is involved is the pumping of hydrogen ions (protons, H^+) across a membrane to create a gradient of concentration and electrical charge. The same basic process operates also in chemo-autotrophs. There are modern bacteria living in the Dead Sea and other very salty environments that trap energy using just one protein embedded in their outer membrane which is able to absorb light and pump protons. So it is not beyond the bounds of possibility that the earliest cells and their precursors (protocells) did something similar. If they were at the surface of the Earth they might have used sunlight; if in the depths of the ocean then oxidation of inorganic or simple one-carbon molecules could have been used. For example, hydrogen (H_2) could have been oxidized by transferring two electrons to sulphur (S), producing hydrogen sulfide:

$$H_2 + S \longrightarrow H_2S$$

Remember there was no free oxygen to carry out oxidation on the early Earth.

2.4.3 The first genetic material

All organisms today have DNA as their genetic material as did, presumably, the universal common ancestor. The problem is that the synthesis of DNA requires the action of several proteins (enzymes), and is chemically difficult. There is much support for the idea that the first genetic material was not DNA but RNA (ribonucleic acid) — protocells might have existed in an *RNA world*. In virtually all modern organisms the information in a gene is copied from the DNA to form an RNA molecule. RNA molecules are crucial for the process of protein synthesis in cells.The idea of an RNA-only world is not pure speculation but is based on a respectable body of evidence and, for interest only, we list some of the evidence in Table 2.3.

Table 2.3 Evidence supporting the view that RNA was the first genetic material.

Item	Evidence
1	RNA can have catalytic activity, acting like an enzyme.
2	DNA building blocks (deoxyribonucleotides) are synthesized *from* RNA building blocks, rather than by an independent pathway, suggesting that RNA came first.
3	Some viruses use RNA as their genetic material and could be molecular fossils of the RNA world
4	RNA plays a central role in several key processes, including protein synthesis (Block 9, Section 11).

By far the most dramatic evidence is item 1 in Table 2.3. The catalytic role of RNA is probably a new idea for you and was a great surprise to the scientific world. Its two discoverers, Sidney Altman and Thomas R. Cech, were awarded a Nobel Prize in 1989. Catalytic RNAs, or ribozymes, have been shown to catalyse, for example, the breakdown of proteins, and the assembly of amino acids into rudimentary peptides (proteins). In 1996 an artificial ribozyme (i.e. one created in the laboratory and not isolated from an organism) was shown to catalyse synthesis of RNA, using nucleotides and an RNA template. So perhaps RNA really could have performed two roles essential for life: carry information encoded in its own nucleotide sequence (the genetic role); and catalyse reactions, including the assembly of proteins (a role now carried out almost exclusively by proteins).

Even this RNA-based system is remarkably complex, however, and it is widely thought that RNA took over the role of information storage from some earlier system. There is no consensus about what this earlier system might have been but, for example, a template based on clay minerals, capable of replication and carrying information, is one suggestion. The RNA-based system was in turn replaced by one in which DNA became the sole genetic material, leaving to RNA the roles concerned with protein synthesis.

This is as far as we shall go in the story of life's origin on Earth. It is still a *very* incomplete story, with precious little evidence and much use of imagination ('speculative hypotheses' in science). You might ask 'why bother?' Does it matter if we do not understand how life arose on Earth? To scientists driven by curiosity, yes, it does matter; this is the stuff of pure science and scientists all over the world are beavering away trying to firm up those speculative hypotheses. There is also the more pragmatic point that we shall be better able to seek out life on other planets, or evidence that life once existed there, if we know how life emerged on Earth.

SA1

Activity 2.5 The origin of life on Earth — Part I

[illegible]

One of the skills being developed in this block is that of gathering information from various sources to help to build an argument and to compare and evaluate these sources of information. The end-of-course assessment might require you to do this for a longer piece of writing, but in this activity you only need to produce a short piece of writing. Activity 2.6 asks you to *plan* a longer piece of writing.

First, look at SA1 (Hazen, 'Life's Rocky Start'). The first part of this paper is largely revision of the items covered earlier in Section 2. The paper then introduces five ideas about the roles played by rocks and minerals in the origin of life. These ideas are summarized on page [illegible] of the paper, and we want you to compare them with ideas discussed earlier in Section 2. Spend no more than about 40 minutes studying the paper.

(a) Which ideas in SA1 (about the role of minerals) are not new but were discussed in the text or papers of Section 2? *Answer in about 100 to 150 words.*

(b) Which ideas in SA1 are new and were not discussed previously in Section 2? In your own words, describe these ideas briefly. *Answer in about 100 to 150 words.*

Activity 2.6 The origin of life on Earth — Part II

(You should spend no more than about 30 minutes on this activity.)

In further preparation for the end-of-course assessment, this activity asks you to *plan* an 800-word answer to the question:

> Summarize and compare the various means by which life might have originated on the Earth.

We have provided advice on planning a scientific account in various places in the course, and you may wish to look back at some of this advice now. In particular, you may find it useful to skim through Activities [illegible] and [illegible] in Block 9, and Sections [illegible] of Chapter [illegible] of SGSG.

Note that the question is about the means by which life might have originated, so you are not expected to include your notes on the dating or the environmental conditions at the time. First, skim through Section 2 of this block, including the articles, noting down relevant points and the section numbers or articles where you found these points. Don't be tempted to make your notes too detailed at this stage; your aim should be to jot down the main points, and you would go back to the section or article for more detail at the stage where you were producing a full draft of the account. Then put the points in a logical order and group them into paragraphs. These paragraphs form the main body of your account. Note that you are asked to *compare* the various means, so to make the differences and similarities between them a part of your planned account should do this. You should also think about how you might refer to the sources of information that you use in your account. Finally, we suggest that you draft the introduction and the conclusion to your planned account — a few sentences for each should be sufficient. The introduction should set the scene and explain your approach to the topic. The conclusion should summarize your main points and any conclusions which you have reached, and this will round off the account.

2.5 Summary of Section 2

Life on Earth originated from a universal common ancestor which probably appeared about 4 000 Ma ago. This first life would have been a single-celled prokaryote whose basic requirements were liquid water, a suitable source (or sources) of energy, and chemical raw materials from which to build new cells.

Evidence about the time of life's origin is mainly geological and of two types: fossil stromatolites show that cyanobacteria-like organisms were in existence 3 500 Ma ago; carbon isotope ratios in rocks dated at 3 800 Ma and 3 850 Ma indicate the existence of autotrophs carrying out photosynthesis and, probably, of chemo-autotrophs too.

Genetic evidence about the nature of the first life is based on comparisons of nucleic acid sequences. Three domains evolved from the universal common ancestor: the Archaea (or Archaebacteria), the Bacteria (which include the cyanobacteria) and the Eukarya from which eukaryotic cells evolved later. These domains must have originated before 3 500 Ma ago.

Conditions on the early Earth were influenced strongly by bombardment from space. This had three effects relevant to the origin of life:

1. Before about 4 200 Ma ago conditions were too unstable to support life, and it is not clear how life survived during the heavy bombardment that ended about 3 800 Ma ago.
2. Comets impacting on Earth could have contributed significant amounts of water to the early oceans and atmosphere.
3. All types of impacting bodies — comets, rocky bodies — might have contributed organic molecules to Earth.

The early atmosphere was not only derived from impacting bodies but also from outgassing of the Earth's interior by volcanoes. It consisted largely of carbon dioxide, nitrogen and water vapour. There was no oxygen and hence no ozone layer, and so much more UV radiation reached the Earth's surface than does at present

Oceans had probably formed by 4 200–4 000 Ma ago and a best guess is that they were saline, contained high levels of reduced iron, iron(II), and had hydrothermal vents.

The surface temperature (GMST) at around 4 000 Ma ago might have been similar to that of today with less power emitted by the Sun balanced by a stronger greenhouse effect and perhaps less cloud cover. A view expounded in Article 3 is that the Earth was actually very cold at this time, with GMST below 0 °C. If this were so, then life may have originated deep in the oceans, probably around hydrothermal vents.

Most scientists believe that life originated on Earth by a process of chemical evolution. However the possibility that life originated on another planet and reached Earth from space (extraterrestrial origin) cannot be ruled out.

The essential features of chemical evolution are that building blocks (monomers) for the large molecules that are used to construct living cells were produced in either the atmosphere and ocean surface by the action of UV radiation and lightning, or deep in the ocean by the action of chemical energy. Monomers reacted further to produce oligomers and then polymers, perhaps catalysed by solid surfaces such as clay minerals. Eventually organized systems appeared that could replicate (protocells) and from these the first cells evolved

Protocells and the first cells were most probably autotrophs. At the ocean surface they could have obtained energy from sunlight as photo-autotrophs; deep in the ocean they would have been chemo-autotrophs, obtaining energy by oxidizing simple molecules such as hydrogen or methane.

The nature of the first genetic material that stored information and allowed protocells to replicate is unknown. It was probably replaced first by RNA, acting as both genetic material and an enzyme (the RNA world), and then by DNA.

Life elsewhere in the Solar System

3

In Block 4 you learned something about the diversity of life on Earth. This is a subject about which a lot is known — and yet the *origin* of life is not fully understood, as you witnessed in the previous section. What *is* known is something of the development and evolution of life on Earth. The relevant information comes not only from the fossil record but also from the genetic evidence found in the nucleic acids of individual species. Living things on Earth, as you will already be aware, span a range of characteristics from highly evolved beings like ourselves, to the primitive organisms from which all life evolved. So, when we talk about 'life elsewhere in the Solar System' we do not necessarily mean entities that we could talk to, or otherwise communicate with (i.e. 'little green men', etc.). We do not even mean to imply life-forms that would be easily visible, or display obvious movement over distances visible to the naked eye. We are really thinking about prokaryotic organisms that would be analogous to bacteria.

Why just bacteria? The reason is that on Earth there is evidence for the continuous existence of bacteria from the time of life's first appearance on the planet.

- What is the age of rocks in which there is evidence for the earliest life on Earth?
- 3 850 Ma, as mentioned in Section 2.

In other words, even though there are bacteria on the Earth *today*, they represent a very primitive class of organism. In contrast, other primitive entities (such as algae, slimes, moulds, plankton, etc.) are more evolved than bacteria, having formed subsequently in geological times. We should contrast the great antiquity of bacteria with the length of time that human beings have been in existence. In Block 4, Section 5.2 you saw that our own species, *Homo sapiens*, has only been around for about 0.15 Ma. If we imagine that all of geological time (4 600 Ma) is scaled to a 24-hour day, this is equivalent to only about the last 3 seconds!

- With all of geological time scaled to a hypothetical 24-hour day, how many hours elapsed between the formation of Earth and the time at which we are certain that life existed?
- The Earth is 4 600 Ma old; the first evidence of life is at 3 850 Ma, i.e. 750 Ma later. Therefore, after formation, nearly 4 hours would have passed before conditions were such that life, as it was, could leave the traces detected today. (Remember that life could have evolved further back in time than 3 850 Ma.)

Bacteria might not sound like terribly exciting life-forms, but it should be realized that on the present-day Earth such organisms are extremely widespread and contribute a large part of the biomass. Indeed, bacteria are found inside humans and other animals, within oilfields, deep within the Earth's crust, in soil and so on. If life evolved elsewhere in the Solar System, it might well have originated in a broadly similar manner to that on Earth. In other words, primitive life-forms on other worlds might well share characteristics with certain terrestrial bacteria; although life could have evolved elsewhere beyond the bacterial stage, we confine our thinking to the most primitive forms.

Let's come clean straight away and say that at the moment there is *no* conclusive proof of the existence of life today anywhere in the Solar System, other than on Earth. At the very least, there might be environments out there of a sort no longer present on Earth but which might help us to piece together a generalized picture of planetary development and thereby more comprehensively understand the conditions that allowed the origin and evolution of life here and perhaps elsewhere. A greater hope is that within the Solar System we shall be able to find the fossilized remains of a primitive environment within which the most primitive of life-forms were just beginning to evolve. Such a find might be the 'missing link' in our quest to understand the origin of life on Earth. The greatest hope is that we will find a living biosphere.

We need to study and evaluate the various habitats within the Solar System that we imagine *could* support life now, or that could have done so in former times. Necessarily, we rather parochially consider life as we know it, i.e. as found on Earth. We shall concentrate on two possible candidates for places where scientists think there is at least a possibility that life may once have evolved (or might even exist today). The bodies concerned are the planet Mars and one of Jupiter's large satellites, Europa. We shall also mention briefly the largest satellite of Saturn, Titan. But first, in Section 3.1, we are going to examine some of the other bodies of the Solar System and evaluate the likelihood of them supporting life. This exercise should give you an insight into how scientists approach an intellectual challenge. Before we go on, you might want to refresh your memory concerning the general layout of the Solar System (see Figure 3.1, and also Block 3, Sections 3 and 5).

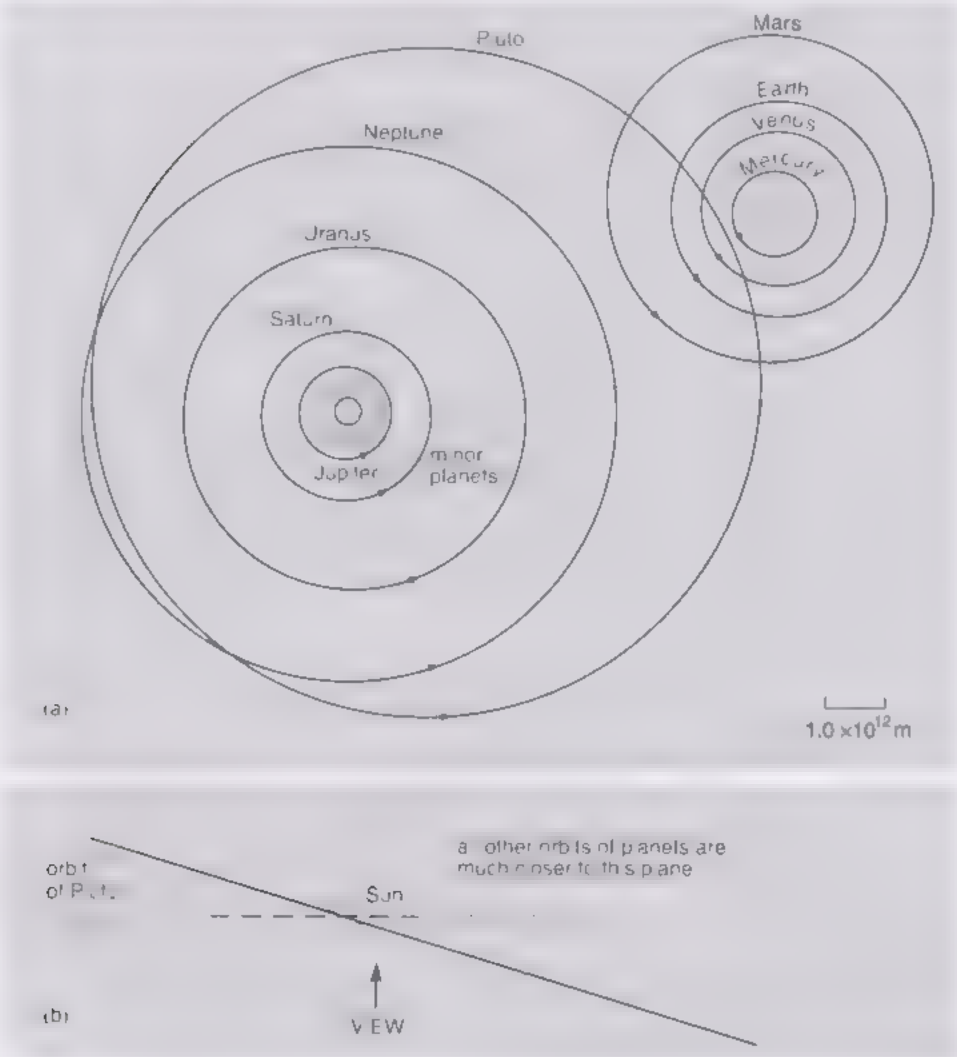


Figure 3.1 General layout of the Solar System: (a) from a viewpoint perpendicular to the Earth's orbit, with an expanded view of the orbits of the terrestrial planets; (b) from a viewpoint in the plane of the Earth's orbit.

3.1 A quick assessment

Let us consider what we need for life (at least as we currently understand it in a terrestrial context).

- What three conditions for terrestrial life were noted in Section 2?
- 1 Liquid water, to act as a solvent and as a reactant.

  2 Light, or other types of electromagnetic radiation, or chemical energy, to construct large molecules.

  3 Supplies of the chemicals (atoms, ions or molecules) needed to construct living cells.

It is also likely that a surface of some kind is needed — particularly a solid surface, even if it is under an ocean. Central to the issue of where to look is the need for liquid water, so we need some way of keeping this in place — in essence, we need a planetary-sized body. This should not be too small, otherwise its gravity would be too low, and any water present within an atmosphere, or as surface liquids, would be lost to space. For a rocky body, the radius needs to be at least about 10^3 km. Alternatively, liquid water could be retained under a sealing layer of ice. Even if we have a sufficiently large planetary body, the surface temperature must be suitable for water to be able to exist in the liquid state. The temperature must be in the range 0 °C–374 °C, though at temperatures above about 130 °C complex carbon compounds are unstable. (Note also that atmospheric pressure also has to be sufficiently high, or liquid water will vaporize very quickly, i.e. boil. At 0 °C the pressure needs to be at least 0.006 bar, and at 100 °C it needs to be at least 1 bar.)

Armed with the above criteria we can begin to appraise the habitability of some of the bodies of the Solar System, and decide where *not* to look It is useful to compare the potential contenders with the Earth, a body which orbits the Sun at a mean distance of 1.50×10^8 km. This is a convenient unit of distance within the Solar System, and it is given a special name — the **astronomical unit (AU)**. The Earth is, of course, a rocky planet, which has an atmosphere and liquid water at the surface. It has a radius of 6 378 km and the atmospheric pressure at the surface is about 1 bar (although variable by a few tens of millibar). Recall that the present global mean surface temperature of the Earth (discussed extensively in Block 2) is 15 °C.

Before we look in some detail at the individual bodies of the Solar System, we will quickly mention here the Moon, which is, of course, the Earth's only natural satellite. It orbits at a distance of about 384 000 km from Earth and has a radius of 1 738 km. In some respects, i.e. its size and similar distance from the Sun as Earth, the Moon may be considered habitable. Indeed, observers of old thought that the dark areas of the Moon's surface were seas. However, as we now know from the Apollo and Luna missions to the Moon, it is by and large dry, and always has been. In other words, the Moon could not ever have supported life. Having said that, there has been much excitement recently with the discovery of relatively minor quantities of water within certain craters at the Moon's poles. Clearly even our nearest neighbour continues to spring surprises — we should bear this in mind as we gaze vast distances across the Solar System at bodies for which we have far less information.

3.1.1 Mercury, Pluto, and beyond

Let's start with Mercury, a small rocky planet (2 440 km radius) with no appreciable atmosphere. Since there is no atmosphere, the Sun's UV radiation reaches the surface and would destroy any organic compounds present. Thus, even if some organic materials had been recently added to the surface of Mercury by comets or meteoroids (as was considered in the case of the early Earth; Section 2.3.2), they would relatively quickly have been broken up. Mercury is the closest of all planets to the Sun (distance 0.387 AU).

- In order to check that you understand the usage of the astronomical unit to express distances, calculate the distance of Mercury from the Sun in kilometres.

- The distance = $0.387\ \text{AU} \times (1.50 \times 10^8\ \text{km AU}^{-1}) = 5.81 \times 10^7$ km.

As a consequence of its proximity to the Sun, the daytime temperatures at the surface of Mercury reach about 400 °C, whereas the negligible atmosphere leads to the night-time temperatures dropping to −180 °C. The large temperature variation makes it impossible to have liquid water at the surface. Also the lack of appreciable atmospheric pressure rules out liquid water.

- Does Mercury look habitable?

- We conclude that Mercury is not an auspicious place to look for life.

At the other extreme, consider the planet furthest from the Sun — Pluto. Pluto is an icy-rocky body 1 150 km in radius, with a tenuous atmosphere, mostly nitrogen (N_2), but with some methane (CH_4) and carbon monoxide (CO). It orbits the Sun once every 248 years. It has a satellite known as Charon, which is about half the radius of Pluto itself! Indeed, Pluto and Charon are now thought to be the most obvious members of a population known as the Edgeworth–Kuiper Belt (and also as the Kuiper Belt). This is a disc-like array of orbiting objects (with diameters equal to Charon, or less) located at distances at and beyond about 40 AU (the orbit of Pluto). Currently about 400 Edgeworth–Kuiper Belt objects have been discovered, but theories of the origin of the Solar System indicate that there are far, far more. Thus, when we consider the notion of life on Pluto we also have to contemplate all the other Edgeworth–Kuiper Belt objects as well.

Since Edgeworth–Kuiper Belt objects are far from the Sun, their surface temperatures are very low, below −230 °C.

- As a quick revision, you may like to recall from Block 5, Section 6.3, the relationship between the Celsius and Kelvin temperature scales, and express −230 °C in the SI unit of temperature.

- To convert a Celsius temperature to the Kelvin scale, 273 must be added to the Celsius value, so −230 °C is equal to (−230 + 273 K), which is 43 K.

These icy-rocky bodies are very 'primitive', representing accumulations of the ices that condensed at the outer regions of the Solar System early in its history. As such they have a direct association with comets — in fact, some comets are thought to originate in the Edgeworth-Kuiper Belt. Because comets are icy bodies that become displaced from their original orbits into ones that bring them closer to the Sun, we can fairly effectively study them using conventional astronomical techniques (some of which you may have encountered if you studied Block 11). In this way we have a good idea about what comets are made from. For instance, we know that they are made up in part of small dust grains (the 'shooting stars' that you can sometimes see in the night sky are mainly dust from comets, the dust entering the atmosphere so rapidly that it makes the atmosphere incandescent). More importantly comets contain organic molecules in abundance. But these are not biologically produced — on the contrary, they were made during abiological (i.e. non-biological) events that have some similarities with the kinds of reactions used for producing polymers and drug molecules that you met in Block 8, Sections 14 and 15.

As well as conventional astronomical techniques, we can also use space probes to study comets when they enter the inner Solar System. Perhaps the most famous example is an ESA mission known as *Giotto*, which conducted a close fly-by of comet Halley in 1986. For the future, missions such as Deep Impact, CONTOUR and Rosetta will continue the investigation of comets. In the case of Rosetta, scientists from the Open University's Planetary and Space Sciences Research Institute are involved with an experiment that will land on the surface of a comet and make in situ measurements of the ices and organic materials using miniaturized versions of instruments that are used routinely in the laboratory.

Further information on the Rosetta mission can be found at http://www.sci.esa.int/science/rosetta whilst some details of the Open University's experiment are at http://pssri.open.ac.uk/research/res-ice.htm (follow the link to the *Modulus* Experiment).*

As you saw in Section 2 of this block, most scientists recognize that it might have been comets, meteorites, and dust that brought organic compounds to the surface of the early Earth. However, while comets, and by extension Edgeworth–Kuiper Belt objects, are a repository of organic compounds, it requires a relatively warm planetary surface to provide the conditions necessary to allow their development into living entities. Thus, we rule out Edgeworth–Kuiper Belt objects, including Pluto, as good places to look for life.

* All websites given in this Block were known to be active in 2004. The use of websites is particularly appropriate in the fast-moving field of the search for extraterrestrial life

3.1.2 The giant planets, and their satellites

Next we shall consider the giant planets, i.e. Jupiter, Saturn, Uranus and Neptune. Their radii range from 71 490 km (Jupiter) to 24 765 km (Neptune).

Question 3.1 Briefly summarize the internal constitutions of the giant planets — a simple sketch would be most appropriate. (Look back to Block 3, Section 5.) ◀

Two of the giant planets, Jupiter and Saturn, are composed predominantly of the elements hydrogen and helium. If you read Block 11 you may recall that the universal nature and formation mechanisms of these elements were discussed in Section 11.6. Hydrogen and helium are venerable constituents of the Universe, with much of their creation having occurred shortly after the Big Bang. When sufficient quantities of hydrogen and helium collect together they can form stars (like the Sun). Lesser quantities, within a stellar system like our own, result in the formation of giant planets. Jupiter and Saturn are large bodies, with relatively small cores (with fuzzy boundaries) composed of elements that are heavier than helium. The temperatures at the surfaces of the cores are several thousand °C, and the cores are liquid throughout. These temperatures are too high for life. As we move outwards from the cores, there is a gradual transition from highly compressed liquids to low-density gases. The temperatures become much lower, but there are no tangible surfaces anywhere, and with no surfaces it is difficult to see how life could originate.

So, is life on Jupiter and Saturn impossible? At face value the answer to this question would appear to be 'yes'. And yet, the atmospheres of the two planets are not exclusively hydrogen and helium. Indeed, they contain all kinds of complex organic compounds, and water is also present. There could be dust particles in the atmosphere as well — Figure 3.2 shows the impact of a comet (known as Shoemaker–Levy 9) onto Jupiter — and comets bear dust. Furthermore, the temperature in the outer atmosphere, at a level where the pressure is a few bars, is a balmy 0 °C

Figure 3.2 Picture of the Shoemaker–Levy 9 impact onto Jupiter. The dark patches are where fragments of the comet entered the atmosphere.

Question 3.2 Do you think it is at least a possibility that life could evolve in the atmosphere of a giant planet like Jupiter? Consider this question with regard to the requirements for life listed at the start of Section 3.1.◀

Uranus and Neptune are also large bodies with very fuzzy cores surrounded by mantles of hydrogen and helium, although the mantles are less massive than in the case of Jupiter and Saturn. Some of the arguments for there being no life on Jupiter

and Saturn can also be applied here. However, it is also worth drawing attention to the distances of Uranus and Neptune from the Sun (19 and 30 AU respectively). This means that they are far removed from the Solar System's main energy source Because we live at the surface of a planet at 1 AU distance from the Sun, we are acutely aware of the necessity of the Sun's radiation for life. For instance, the ecosystem and food chains within which we, as humans, partake are fundamentally reliant on the Sun's radiation, through the photo-autotrophs (Section 2.4.2). However, there are organisms on Earth living in the deep oceans and at depth within the crust which derive all their energy from non-solar sources — the chemo-autotrophs (Sections 2.2 and 2.4.2). Thus, as far as they are concerned there need be no Sun. The critical issue is whether solar radiation is necessary for the *origin* of life. This is a hotly debated subject as you saw in Section 2, and one for which it is impossible to give an answer. You should, however, appreciate the significance of this issue.

We shall proceed on the basis that life on the giant planets looks unlikely. However, their satellites are a different issue. Each planet has a number of satellites, and there are a few that are relatively large, being equivalent in size to Mercury, or to the Earth's Moon (1 738 km radius), i.e. Io, Europa, Ganymede, Callisto (all orbiting Jupiter; Figure 3.3a), Titan (Saturn; Figure 3.3b) and Triton (Neptune; Figure 3.3c). Thus, in the context of life in the Solar System these bodies should be added to the list of potentially interesting places to consider. For reasons that we do not have space to go into here, scientists discount all of these candidates except Europa and Titan. However, all of these bodies are fascinating in their own right and it will not be until spacecraft visit them and make detailed surveys that we shall have a reliable picture about their potential for supporting life. We shall return to Europa and Titan in Section 3.2

(a)

(b)

(c)

Figure 3.3 Collage of giant planet satellites, to correct relative sizes. (a) Io, Europa, Ganymede, Callisto. (b) Titan. (c) Triton

3.1.3 Venus

Now let us consider some basic facts about Venus — Earth's 'sister' planet. Venus has a radius of 6 052 km, so is very similar in size to the Earth, and is some 0.723 AU from the Sun. The density of Venus is about the same as that of the Earth, and so in terms of bulk chemical composition it is very similar to the Earth. In the light of its proximity to the Earth, and its similar size and density, it is fair to assume that Venus formed from the same kinds of materials as the Earth (see Block 3, Section 5 for further details). Intuitively, you may have expected the environment at the surface of Venus to be similar to that on Earth. And yet it is completely different.

The surface of Venus is a blistering 460 °C, a consequence of a powerful greenhouse effect in the atmosphere (Block 2, Sections 5.4.3 and 10.1). Such temperatures do not allow the survival of liquid water at the surface of the planet. Moreover, the atmosphere itself is very dry — there is very little water vapour. So, why did it all go wrong on Venus?

- In terms of trying to understand the present day surface conditions on Venus and Earth, what is the key difference between the two planets that you could imagine might have been contributory?

- Venus is closer to the Sun than Earth. As such, it would be expected to receive correspondingly more solar radiation.

Venus intercepts about twice as much solar radiation as the Earth. If, in the distant past, there was water at the surface of Venus, then it would have evaporated far more readily than water on Earth. In the atmosphere, water is split into hydrogen and oxygen by solar UV radiation, and so the water on Venus was readily exposed to this fate. The hydrogen escaped to space, and the oxygen combined with the surface or with volcanic gases. The absence of oceans on Venus through much or all of its history prevented the formation of carbonate rocks, thus maintaining a high atmospheric content of carbon dioxide and a strong greenhouse effect. The rising surface temperatures drove much carbon out of rocks into the atmosphere to add to the carbon dioxide, and this further increased the greenhouse effect.

The results of these processes are (i) that Venus has an atmosphere mainly of carbon dioxide, with a mass about 100 times that of the Earth's atmosphere, and (ii) that from very early in its history the surface has been very hot. These factors rule out life today and in the past. There are some other interesting and relevant details about the atmosphere of Venus, notably the presence of sulfuric acid rain (which never reaches the surface because it is too hot). All in all, there are a number of factors that seem to mitigate strongly against life having evolved on Venus.

Among the major planets (other than the Earth), that leaves Mars, and this is one of the prime candidates for life.

3.2 The prime candidates

The prime candidates are Mars and (as mentioned in Section 3.1.2) Europa, and we shall shortly evaluate the evidence that can be used to address the question of life on these bodies. Firstly though, we want to consider in a little more detail exactly what it is we are looking for.

5

Activity 3.1 The search for extraterrestrial life — Part I

(You should spend no more than about 40 minutes on this activity.)

Introduction

In this activity you will read the first of two extracts from 'Article 5: The search for extraterrestrial life', which appeared in the popular scientific magazine *Scientific American* in 1994.

[illegible]

The *Galileo* results obtained from observations of the Earth show us quite clearly that we know how to spot the signs of life from relatively few simple measurements. So far we have not observed any of the requisite signals from any other bodies in the Solar System, though scientists are still not 100% sure that life does not exist beyond the Earth. We really need to go and visit the various planets and satellites in order to obtain a more conclusive picture.

Before tackling the various observations of Mars and Europa we want to consider Titan — the largest satellite of Saturn (Figure 3.4). You read in Section 2 about some of the ideas regarding the origin of life on Earth, and we have alluded to the fact that our knowledge remains incomplete because of several gaps in the evidential record. Recall that the Earth harboured life by about 3850 Ma before present; we assume that this life did not exist prior to the formation of the Earth at 4600 Ma before present. The vital period, in which life got started, coincides with a time interval that is effectively not represented by the geological record on Earth. In order to circumvent

Figure 3.4 View of Titan from the *Voyager 2* spacecraft. The satellite is covered by a smog, known as 'Titan's haze', which arises from photochemical reactions involving molecules such as N_2 and CH_4.

Figure 3.5 Artist's impression of the *Huygens* probe descending towards the surface of Titan

this lack of evidence there have been many bold experiments over the years that attempt to simulate conditions on the early Earth, and there have been many more directed towards assessing how the sub-components of living entities may have been formed or evolved (e.g. membranes and cells, the process of replication, etc.). However, it is a fact that 'life' has not thus far been re-created from assumed starting materials in a test-tube. As such, any further information that can be brought to bear on this issue is constantly being sought. The Solar System provides us with many insights into the processes that we seek, and a most appropriate example can be found in the case of Titan

With a radius of 2575 km, Titan is the second largest satellite in the Solar System (after Ganymede). For comparison, recall that Mercury has a radius of 2440 km and the Earth's Moon 1738 km. What makes Titan so special for our attempts to understand the origin of life on Earth is that it is the only body in the Solar System other than the Earth that has a 'thick' nitrogen atmosphere. The surface pressure on Titan is almost one and a half times that on Earth. We know that Titan's atmosphere contains about 95% nitrogen, but no oxygen; it also contains a variety of hydrocarbons, which rain down onto the surface whereupon they may interact with water (following impact events for instance). In some respects, this natural laboratory

may be a very important analogue of the early Earth. It is inevitable, therefore, that we would want to study this fascinating body in more detail. Although very little of the surface can be seen with optical telescopes, we shall find out more about this interesting place in 2005 when the *Cassini* spacecraft goes into orbit around Saturn and releases the *Huygens* probe to descend through the atmosphere of Titan (Figure 3.5). Further information about the mission can be found at the following websites:

http://saturn.jpl.nasa.gov/cassini/english (for the *Cassini* orbiter)

http://www.esa.int/specials/cassini-huygens/index.html (for the *Huygens* probe)

SA2

Activity 3.2 Lifting Titan's veil

You should spend no more than about 60 minutes on this activity.

The six extracts included in Supplementary Article 2 (SA2) come from a book entitled *Lifting Titan's Veil* by Ralph Lorenz and Jacqueline Mitton (published in 2002). To some extent the book, which is written in a fairly quirky but nonetheless entertaining style, follows the career of Lorenz from his early days as an engineer working at ESA on the Project Team for the *Cassini–Huygens* space mission to Saturn and Titan, to his PhD project working on specific aspects of the mission, to his post-doctoral work and ultimately to the launch of *Cassini–Huygens* and what [illegible] ought to be from the mission as a whole. This odyssey is interesting in its own right and may provide inspiration, or even pointers, for Open University students contemplating research careers. One of the things you will learn while reading the extracts is that the academic team responsible for the specific experiment with which Lorenz was formerly involved has now relocated to The Open University to join the Planetary and Space Sciences Research Institute. This particular experiment, the *Surface Science Package* (known as SSP), will travel with the *Huygens* probe down through Titan's atmosphere and eventually make measurements of the physical properties of the satellite's surface. The results from this activity, now scheduled to take place in early 2005, are eagerly awaited!

Note that you can find additional information about the prebiological organic chemistry on Titan in Article 8, but this is not necessary for the activity as a whole.

You should now read the first four extracts from SA2; the remaining two extracts may be used in the end-of-course assessment (ECA).

Question 3.2.1 In the extracts you will have read about a substance known as 'tholin'. This is an operational term for a type of material that can be produced in the laboratory by experiments designed to simulate the photochemistry believed to take place in the atmosphere of Titan. Briefly review the processes taking place in Titan's atmosphere that could lead to the production of tholins. *(150–200 words)* ◀

Question 3.2.2 Explain how meteorite/comet impacts onto the surface of Titan may have implications for the formation of what we might think of as biological precursor molecules such as amino acids. *(150–200 words)* ◀

3.2.1 Mars

Mars has, for many years, held a special relationship with humankind. Indeed, the planet has featured in many works of fantasy and science fiction, where the planet is depicted as being inhabited by aggressive and expansionist aliens. Psychologically we are already conditioned to the notion of life on Mars — but what is the reality?

Mars is the next planet out from the Sun after the Earth (Figure 3.6). It is a rocky body, 3 397 km radius, with a thin atmosphere of carbon dioxide, and surface temperatures that can reach 20 °C on a very good day. The surface pressure, however, is close to 0.006 bar, the minimum to prevent liquid water from vaporizing very rapidly (boiling). There is no evidence of liquid water on Mars today (though there is water ice at the surface).

Mars hit the headlines in 1996 after a NASA press conference was convened to announce the publication of a scientific paper claiming that biological microfossils had been discovered in a martian meteorite known as ALH 84001. This was accompanied by a Presidential statement by Bill Clinton saying that 'if this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered'. Powerful stuff indeed! We shall have a look at this paper later, but first we shall look at a second extract from Carl Sagan's *Scientific American* article.

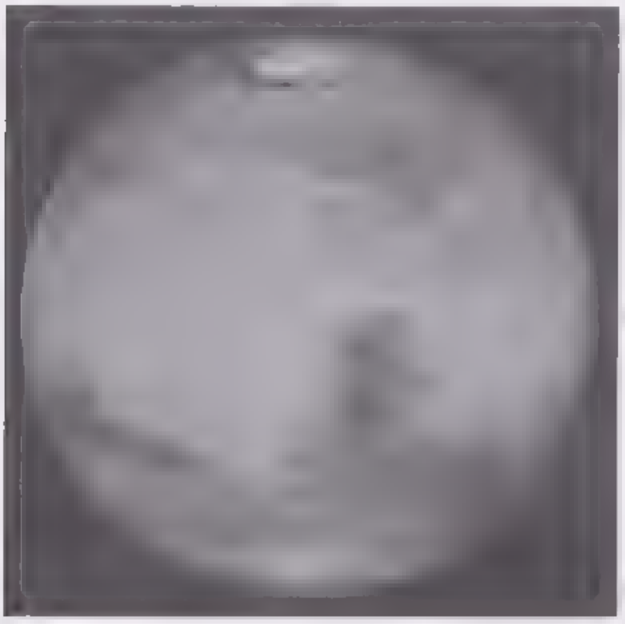


Figure 3.6 One hemisphere of Mars, with the north polar cap visible at the top

5

Activity 3.3 The search for extraterrestrial life — Part II

(You should spend no more than about 15 minutes on this activity.)

Introduction

Within Extract 2 from Article 5 you will find references to meteorites from Mars. As well as originating from minor planets (asteroids), meteorites can also come from planetary bodies. Thus far, scientists have examples found on Earth of meteorites which originate from the Moon and Mars. As you might imagine, the study of martian meteorites is an extremely valuable approach to understanding the planet (more of this later). Note that martian meteorites are also known as SNC meteorites, which is how they were classified (S, N and C standing for three subgroups, named after the initial letters of the places where one in each subgroup was found) before they were recognized for what they are.

You should now read Extract 2 from Article 5.

Question 3.3.1 List the results of the *Viking* experiments of 1976 that were designed to test for life on Mars, and that at first sight appeared positive.

The first thing to consider about the *Viking* experiments is why they were done in the way that they were. To appreciate this you need to step backwards and ask yourself, 'how do you test for the presence of life?'. An alien spacecraft landing on Earth would have no difficulty assessing the presence of life — we have already discussed the *Galileo* results that show, from afar, the presence of terrestrial life. But let's pretend the alien spacecraft was only fitted with a camera. On the ground it would be fairly easy to observe signs of life with the camera, if it was in the right place. But what if the spacecraft landed in the middle of the Saharan desert, or in Antarctica? You would argue that it would be unwise to have chosen such locations in the first place. But consider that the *Viking* landers could not just have landed *anywhere*. Their

landing sites were chosen partly on the basis of technical considerations — not least of all they had to be fairly flat, with not too many obvious obstacles that might cause the spacecraft to land awkwardly. More than twenty years later, in July 1997, *Pathfinder* arrived at the planet with the same constraints on landing site selection – in fact the *Pathfinder* was put down only a few hundred kilometres from one of the *Viking* sites (Figure 3.7). And of course, it was obvious to scientists in the *Viking* era that Mars was not *teeming* with life. If anything they supposed that the martian surface might be analogous to that of, say, the surface of the Earth 4 000 Ma ago.

Figure 3.7 Panorama of surface of Mars taken by *Pathfinder* 21 years after the *Viking* missions. This site has been named after Carl Sagan.

So the *Viking* scientists were faced with setting up a few simple experiments, which could be performed with instruments that had masses of a few kilograms and that used just a few watts of power. Because Mars is so far away from the Earth, the time it takes for radio signals to travel back and forth between the two planets is several minutes. So, it is not possible to control experiments interactively from the ground. Rather, they have to run autonomously. The *Viking* team reasoned that materials from a purely sterile planetary surface (even in the presence of some nutrients) would not affect the constitution of any gases in contact with them — hence the gas exchange experiment. For this a robotic arm from the lander spacecraft grabbed a sample of surface materials, put it inside a container along with gases from the local atmosphere, and added a supply of nutrients. A positive result, deemed to be the observation of a change in the composition of gases, was considered to imply that there was metabolic activity within the soil sample. In other words, this experiment appeared to prove there was life on Mars! In the second experiment, organic foodstuffs were added to the soil These foodstuffs, taken from Earth, had been specially prepared so that they contained ^{14}C, the radioactive form of carbon.

In the *Viking* experiment the ^{14}C was used, as a tracer. In fact this is an approach used in many instances on Earth. For example, consider the carbon cycle introduced in Block 2, Section 8. Because ^{14}C is radioactive, it decays with time If we want to assess how carbon moves within, say, a biological system, we would first add ^{14}C to one part of it. By then looking for ^{14}C concentrations above the natural background level in other parts of the system, we could then ascertain where the added ^{14}C had ended up.

Returning to the *Viking* experiment, it would be anticipated that within a purely sterile environment nothing would happen, i.e. the ^{14}C-enriched foodstuffs should stay where they were put within the soil. And yet, with time, ^{14}C was observed in CO_2 gas evolved from the soil. So, the results of this experiment seemed to suggest the presence of life as well, life which was converting the foodstuffs into CO_2. Finally, a new sample of soil was deliberately exposed to CO_2, again with a ^{14}C tracer, the rationale being that with no life present, nothing should happen. But the CO_2 was removed into the soil — something had to be doing this. Was the removal due to martian microbes?

Probably not! In Extract 2 from Article 5 Sagan states that one of the reasons that the presence of life-forms on Mars was discounted was that the apparent metabolic activity took place under a wide range of conditions. At the time microbiologists thought it unlikely that microbes would be active under such variable conditions. This might be largely true, but since the time of *Viking*, a lot more has been learned about terrestrial micro-organisms and their ability to adapt to what would have once seemed like hostile environments. For instance, there are now examples of bacteria than can survive (even thrive) in water at temperatures above 100 °C. These are called

thermophilic bacteria, or thermophiles (Section 2.2); we shall consider them further when we discuss Europa. So, hostile conditions in themselves are not a good argument against the survival of life. However, there is a very good reason why it is thought that the *Viking* results did not adequately demonstrate the presence of life on Mars. And that is because the landers also failed to detect any indigenous organic compounds in the martian soil.

Although there were positive results from the *Viking* biology experiments (to all intents and purposes indicating the presence of life), there was not the slightest shred of evidence for any organic molecules (and by extension, no evidence for any living things), and so the biology experiments had given completely misleading results. The second extract from Article 5 explains this dichotomy. In the immediate aftermath of the *Viking* programme scientists considered the matter closed. However, the subject is being debated once more (and in some cases by the same scientists!). Why is this? We have already pointed out that advances have been made in understanding the distribution of life on Earth. In a sense this is like uncovering new evidence during a legal proceedings — what we have now is a re-trial. But this is not the only reason. In the decade after *Pathfinder* a veritable armada of spacecraft will visit the planet to tackle once again the question of life on Mars. This programme will (hopefully) culminate in 2005 with the launch of a mission that will return samples to the Earth. So, scientists need to prepare themselves for this event.

For now, though, we are left pondering the question of whether life ever got started on Mars. One way in which we can attempt to answer this question is to study martian meteorites. There are more than 20 martian meteorites known, with new samples turning up about once a year. However, note the following statement from Article 5:

> A few researchers have made tentative claims of finding organic matter in a class of meteorites (the SNC meteorites) that are thought to be bits of the martian surface blasted into space during ancient impacts. More likely, the organic material consists of contaminants that entered the meteorite after its arrival on our world. So far there are no claims of discovering martian microbes in these rocks from the sky

Activity 3.4 Search for past life on Mars: possible relic biogenic activity in martian meteorite ALH 84001

[illegible]

In Activity 3.5 you will read a complete article on the same subject, but this time written for a more general audience — a piece of scientific journalism. Since scientists cannot be experts in all fields, but still like to try to keep up with advances in many fields, they frequently turn to such articles. These will have been written by experts who are familiar with the subject in question, but who are not necessarily the authors of the original work.

What you need to extract from Article 6 is the conclusion that a martian meteorite might contain evidence for life on Mars in the distant past. It was a controversial paper that caused much media and public attention. You will notice that there are nine authors — it is often the case that a ground-breaking discovery will involve many scientists working together. It is also testimony to the multidisciplinary nature of some aspects of scientific work, which in the present example involved workers from four scientific institutions.

There are some technical terms that you need to know about.

1. You met hydrocarbons if you studied Block 8, Section 12, and should recall that they are chemical compounds made out of carbon and hydrogen. Polycyclic aromatic hydrocarbons are produced by combustion — you will encounter them in the blackened surface of burned food! They are also present in car exhausts.
2. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are types of microscopy that provide very high magnifications and use beams of electrons for illumination rather than light. You can see examples of SEM and TEM images in Block 9 (SEM: Figure [illegible]; TEM: Figure 2.3).

You should now read Extracts 1 and 2 from Article 6.

Question 3.4.1 List the five lines of evidence given in Article 6 which the authors cite as being compatible with the existence of past life on Mars. ◀

7

Activity 3.5 Life on Mars?

You should spend 1 hour on this activity.

[illegible]

In order to try to provide a balance to what was a controversial paper, we now ask you to read Article 7, 'Life on Mars?', which appeared as part of the 'Focus' section of the popular science journal *Astronomy Now*. It is written by Ian Wright (an Open University Course Team member) and Monica Grady (curator of the national meteorite collection, Natural History Museum, London). The paper gives some background to meteorites, and the reasons why scientists think SNC meteorites come from Mars (a perennial question!). It also mentions some of the research carried out on martian meteorites at the Open University. The key thing to appreciate from the paper is the caution it injects into the debate.

You should now read Article 7.

Task 1 Martian meteorites

In about 100 words each:

(a) outline the argument for suggesting that some meteorites have come from Mars;

(b) state why many scientists doubt that the features of the martian meteorite ALH84001 have a biological origin.

The papers you have just read about the possibility of fossilized microbes in the martian meteorite ALH 84001 are now several years old. So, it would be entirely logical to ask what developments have ensued in the intervening years. In brief, there has been an explosion of interest in Mars, life on Mars, martian meteorites, and ALH

84001 in particular. There are many excellent resources (and some dubious ones!) on the Web that are dedicated to these issues. Amongst some of the most informative are. http://www.lpi.usra.edu/expmars/expmars.html for basic facts about Mars and its exploration; http://www.lpi.usra.edu/lpi/meteorites/the_meteorite.html for information about ALH 84001; and http://www.lpi.usra.edu/publications/abstracts.html for links to scientific abstracts from lunar and planetary science conferences.

In essence, although evidence has begun to pile up, interpretations and opinions have become increasingly polarized. Most scientists do not accept that the observations of features or chemical signals in ALH 84001 constitute evidence for past life on Mars. In contrast, a few die-hards believe the converse, i.e. that the evidence is entirely commensurate with past life. This is science in action. It seems clear to most people involved that the issue will not be adequately resolved until either samples are returned to Earth from Mars by space missions (perhaps by 2015), or the planet is explored properly by humans (perhaps 2030–2050).

3.2.2 Europa

We now meet the second body in the Solar System that is a candidate for life — one of the satellites of Jupiter, Europa. This satellite was studied in detail by the *Voyager 2* spacecraft, which showed this body of 1 570 km radius to have an apparently smooth, featureless surface, described as being 'as smooth as a billiard ball' (Figure 3.3a). This indicates recent resurfacing. *Voyager 2* also showed that the majority of the surface of Europa was made of water ice. New images of Europa, taken by the *Galileo* spacecraft (Figure 3.8), show that the surface ice of the satellite is cracked, further demonstrating that there is continuing internal activity on the body. The conclusion is that the ice crust is being renewed from underneath by warm ice or, more importantly, liquid water. Indeed, there could be regions on Europa that are both warm enough, and sufficiently wet, to host life.

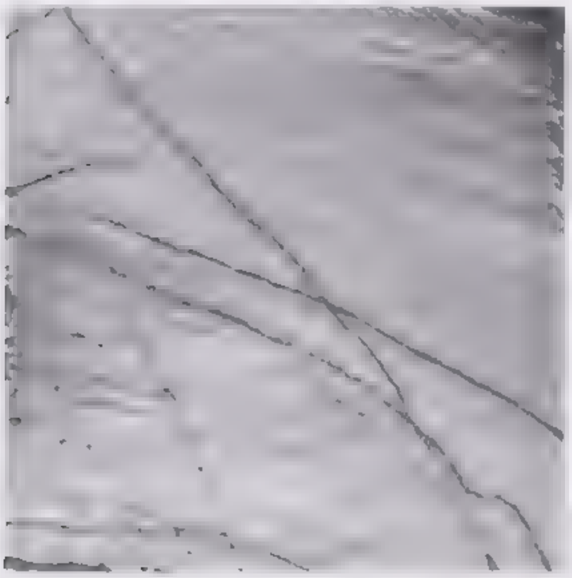


Figure 3.8 *Galileo* image of the cracked, icy surface of Europa. The area of view is 1 260 km across.

Question 3.3 How could life on Europa have undergone a 'cold start'? ('Cold Start' is the title of Article 3.) ◀

It might be tempting to conclude from the smooth surface laced with cracks, and the nearly pure water ice composition, that Europa is a giant ball of ice. But the density of Europa is 3 040 kg m^{-3}, which is much greater than that of water ice.

- You have already encountered the density of liquid water, which is 1 000 kg m^{-3} (at 0 °C and 1 bar). How does the density of water as *ice* at 0 °C and 1 bar, compare with 1 000 kg m^{-3}?

- The density of water ice is slightly *less* than 1 000 kg m^{-3}.

This is why ice floats on liquid water (Block 1, Section 4.2). Indeed, ice would also overlay a liquid water layer in the somewhat different temperatures and pressures on Europa. But on the basis of the known density of Europa it cannot be composed largely of pure ice, nor largely of liquid water. Indeed, to have a density as great as 3 040 kg m^{-3}, Europa must be composed largely of silicates. There are a number of models that describe the internal constitution of Europa, which we shall consider after Activity 3.5. Note that it is the inside of the satellite that is the most relevant feature when considering the possibility of life on Europa.

Activity 3.6 Europa: prospects for an ocean and exobiological implications — Part I

[illegible]

Question 3.6.1 [illegible]

The three models alluded to in this paper, which was written several years ago, nicely exemplify a situation that arises in the course of scientific endeavour. Currently, we do not know what the interior of Europa is like. However, on the basis of the available evidence, the observations can be interpreted in three different ways, any of which could be correct. In part of the article not reproduced here, it is concluded that the thin ice model looks unlikely. The key observational evidence that mitigates

against the thin ice model is the fact that there are very few visible craters. In a model with solid rock close to the surface (as it would be in the thin ice model) it is anticipated that the effects of an impact would be readily recorded. In contrast, an impact into thick ice, or an ice–ocean layered structure, although visible immediately afterwards, would nonetheless disappear as the surface ice flowed back into shape (much as a glacier flows down a mountain). The conclusion of the article regarding an appraisal of the models of Europa is that 'the presence of a liquid ocean appears plausible but not proven'.

- Why do you think that the presence of a liquid water ocean on Europa would be exciting for planetary scientists?

- Liquid water is one of the prerequisites for life. An ocean of liquid water on Europa, if confirmed, would open up the *possibility* that there is some form of life there.

As stated above, the paper used in Activity 3.6 was written several years ago. So, has it stood the test of time? Inevitably there have been advances in modelling and observations, including many more results from the *Galileo* space mission. But, as with similar ventures in science, the advances that have been made are very much down in the detail. To illustrate this we give below quotations from two papers from the weekly science journal *Nature*.

From M. H. Carr et al. (1998) volume 391, pages 363–365, 'Evidence for a subsurface ocean on Europa':

'It has been suggested that Europa's thin outer ice shell might be separated from the moon's silicate interior by a liquid water layer, delayed or prevented from freezing by tidal heating… The detailed morphology of the terrain [i.e. mobile 'icebergs', as described in the paper] strongly supports the presence of liquid water at shallow depths below the surface, either today or at some time in the past'.

From P. M. Schenk (2002) volume 417, pages 419–421, 'Thickness constraints on the icy shells of the galilean satellites from a comparison of crater shapes':

'Here I present measurements of depths of impact craters on Europa … that reveal two anomalous transitions in crater shape with diameter … The second transition is attributed to the influence of sub-surface oceans …, which constrains Europa's icy shell to be at least 19 km thick'.

The selected quotations seem reasonably in accord with the ice–ocean model considered in Activity 3.6. Most scientists in the field now accept that there probably is indeed an ocean of liquid water on Europa. As such, you should be aware that nowadays reference to a 'thin ice model' generally means one that involves a thin ice crust on top of a liquid ocean (unlike the thin ice model in Activity 3.6, which did not). Indeed, the most vigorous debates concerning Europa are now directed towards the thickness of the icy crust. This has ramifications, not only for the possibility of life on Europa (which you will study in Activity 3.8), but also the possibility that we will ever be able to study it. Although engineers can conceive of ideas for space missions that may be able to penetrate a kilometre or two of ice, 19 km presents the most awesome of challenges. Intriguingly, this same sort of problem is currently exercising the minds of scientists and engineers who want to sample a freshwater lake (Lake Vostok) beneath 4 km of ice in Antarctica. Here, it is suspected that previously unknown primitive life forms might exist, which have been cut off from the surface environment for perhaps millions of years. Should they exist, study of these entities will have a direct bearing on life in a wider Solar System context and possibly be of relevance to some aspects of the environment on Europa.

For more information on Europa check the following websites:

http://www2.jpl.nasa.gov/galileo/europa/

http://www.nineplanets.org/europa.html.

Activity 3.7 Europa: prospects for an ocean and exobiological implications — Part II

(You should spend no more than about 15 minutes on this activity.)

Introduction

Extract 2 from Article 8 is about the quantity of organic compounds that might be in a liquid water ocean on Europa.

The text which, in the complete article, precedes this extract, is a justification of why the overall chemical composition of Europa is considered to be like that of carbonaceous chondrites. These are meteorites that are chemically very 'primitive' and, as their name implies, they contain carbon. Carbonaceous chondrites are comparatively rare in meteorite collections, but it is thought that they have remained unaltered from their time of formation 4600 Ma ago (hence 'primitive') and that they are representative of the kinds of materials which aggregated to form planets and satellites, etc. The important thing to realize here is that carbonaceous chondrites (like other meteorites) are available for study on Earth. Thus, if Europa is made of carbonaceous chondrite-like material, then its overall chemical composition can be assessed *without* actually going there and measuring it.

The authors continue their discussion of Europa's composition by a comparison with type II carbonaceous chondrites. It is not necessary to understand the significance of this subdivision.

An 'acid insoluble carbonaceous phase' is a complex mixture of organic compounds that is inert to acid attack (hence 'acid insoluble'). Indeed, this is a property that is exploited for its isolation in the laboratory, where meteorites (or terrestrial rocks) are treated with acids to dissolve silicates, carbonates, sulfates, etc., leaving behind a residue of inert carbonaceous material. On Earth we find acid insoluble carbon in sediments. Coal is an example of a carbonaceous material that is acid insoluble; oil shale, which is produced by the action of sediment burial and subsequent heating, is another example. In both cases oil and coal are altered products of decayed biological materials (easily assessed using techniques of microscopy or other analytical methods). But acid insoluble carbon is not necessarily formed by biological processes. Indeed, polycyclic aromatic hydrocarbons (see Activity 3.4) can be produced by purely abiological processes; when concentrated and heated, they transform into acid insoluble components. It is an abiogenic origin that most satisfactorily describes the acid insoluble organic compounds in carbonaceous chondrites.

'Acid *soluble*' organic compounds are relatively simple molecules that are soluble in solvents (e.g. acids themselves, or water, or methanol, etc.). The acid-soluble compounds in carbonaceous chondrites are also abiological in origin and though biological 'signatures' are sometimes seen, these *always* result from contamination by terrestrial compounds.

The important things to try to understand from Extract 2 are:

- the relationship proposed in the article between Europa and type II carbonaceous chondrites
- that carbonaceous chondrites can bring biologically important materials to Solar System bodies.

The questions and text below will help to consolidate these ideas.

You should now read Extract 2 from Article 8.

What are the principal constituents of type II carbonaceous chondrites?

Table 6.2 in Article 8 shows that type II carbonaceous chondrites are composed of SiO_2 (27.57%), MgO (19.18%), C (2.46%), H_2O (13.35%), and S (3.25%). (These are percentages by *mass*.)

Note that the SiO_2 and MgO are present in minerals, such as silicates. A large part of the H_2O is also present in minerals in the form of hydrated components (very much like clay minerals). The S is present in sulfates and sulfides.

- What makes carbonaceous chondrites so important as far as extraterrestrial life is concerned?
- Carbonaceous chondrites contain a significant amount of organic compounds.

The detailed carbon inventory of one particular type II carbonaceous chondrite (known as 'Murchison') is shown in Table 6-3 of Article 8.

- What is the main carbon-bearing constituent of Murchison?
- An acid-insoluble carbonaceous phase.

In addition to the acid-insoluble organics, carbon in Murchison can be seen to exist in oxidized forms (carbonates and CO_2), but almost exclusively the former. The carbonates represent inorganic mineral components. The rest of the carbon inventory is in the form of acid-soluble organics, i.e. those compounds detailed in the rest of Table 6-3. (Murchison also contains several hundred p.p.m. of diamonds of nanometric dimensions and much larger micrometric-sized silicon carbide crystals. But that's another story!)

Murchison, like other type II carbonaceous chondrites, contains biologically important compounds. As well as amino acids (c. 20 p.p.m.), there are purines (about 1 p.p.m.) and pyrimidines (about 0.05 p.p.m.). But even though the overall carbon content of Murchison is 2 to 2.5% by mass (i.e. 20 000–25 000 p.p.m. C), these biologically important molecules only constitute overall about 20 p.p.m. of the carbon, i.e. only about 0.1% of the total mass of carbon.

Question 3.7.1 The surface of the primitive Earth was bombarded between 4600 and 4000 Ma ago by materials which probably had an overall composition not very different from that of the carbonaceous chondrites. Assuming this was of the type II variety, what kinds of biologically auspicious materials would have been deposited on to the primitive Earth at this time? ◀

Question 3.7.2 Assuming that the composition of Europa was similar to that of type II carbonaceous chondrites, how does the proposed ocean of the satellite compare with the Earth's surface in terms of carbon content and what is the likelihood that life could have developed on Europa? ◀

Activity 3.8 Europa: prospects for an ocean and exobiological implications — Part III

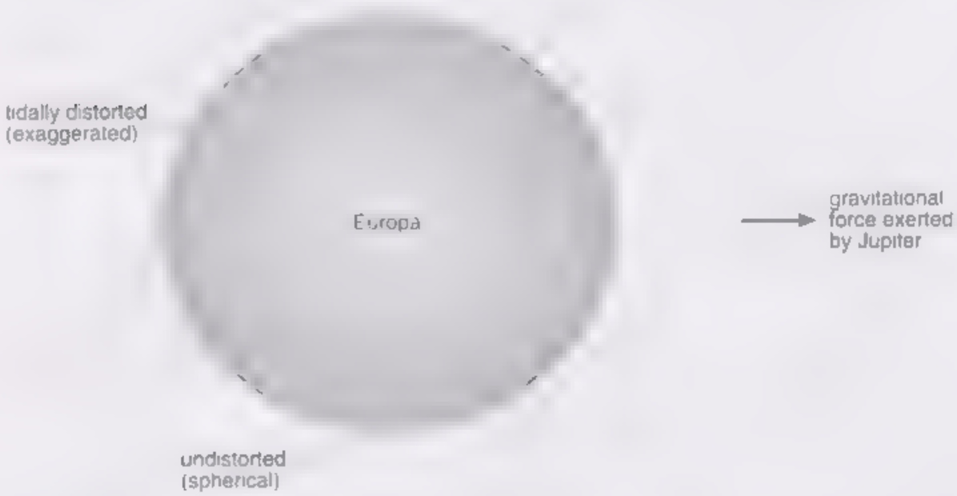
(You should spend no more than about 15 minutes on this activity.)

Europa thus probably has two important prerequisites for life: liquid water and the availability of elements that can be utilized by biological entities. What about a suitable supply of energy for life? The final extract from Article 8 contains some important information on this topic. Tidal heating and redox potentials are mentioned. These will be explained after you have read the extract.

You should now read Extract 3 from Article 8.

Tidal heating, as the name suggests, results from tides in an object. A tide is a gravitational distortion in the shape of an object. In the case of Europa, the gravitational force of Jupiter distorts the satellite as shown in Figure 3.9. As Europa orbits Jupiter its distance from Jupiter changes slightly because of its slightly elliptical orbit. Consequently the distortion also changes slightly, in magnitude and in orientation. Therefore, the satellite is constantly being flexed. This flexing generates heat in the interior, and is an essential supplement to radiogenic heat from the interior for the sustenance of a liquid ocean. (The gravitational force of the Moon and the Sun distort the Earth's oceans to give the familiar ocean tides. The tides rise and fall because the oceanic tidal bulge is aligned with respect to the Moon, whereas the Earth beneath the oceans is rotating with respect to the Moon. The whole body of the Earth is also distorted, though by less than its oceans.)

Figure 3.9 Tides in the whole body of Europa (greatly exaggerated).



The combined effects of tidal and radiogenic heating in Europa also create hot spots on the ocean floor (Article 8, Extract 3). These may be analogous to environments on Earth where hydrothermal activity within the oceanic crust above magma chambers produces emergent hot springs (Block 3, Section 14.1.2). Where these are released into Earth's oceans there exist oases capable of supporting life (even though the local temperatures may be in excess of 100 °C). Indeed, life on Earth might have started around such hydrothermal vent systems (Section 2.2 of this block). Today they sustain chemosynthetic bacteria. These are bacteria that derive all their energy from the reaction of sulfur and hydrogen compounds that are released from the vents. They are thermophilic and closely resemble the most ancient prokaryotes. In other words, they are very primitive organisms, representing the kind of bacteria that may have been present on the early Earth — the Archaea (Section 2.2). Their utilization of sulfur is testimony to their ancient character.

It seems entirely possible that an environment similar to that in which thermophiles thrive on Earth could exist around deep oceanic vents on Europa. If we accept the model of Europa that shows a link with type II carbonaceous chondrites then clearly sulfur would be available in abundance. The total sulfur content of Europa is equivalent to 1.6×10^{21} kg, which is about the same as the quantity of carbon. Also, since sulfur is present in both oxidized and reduced forms (sulfates and sulfides respectively) there would exist a chemical source of energy for the chemosynthetic bacteria — this is the redox potential in Extract 3. This would be ideally suited for utilization in metabolic reactions early in Europa's history.

In conclusion, Europa appears to have all the necessary requirements for life. It may have an ocean of liquid water, an abundance of biologically important elements, and energy sources in the form of sunlight and chemicals from submarine hot springs. One group of micro-organisms on Earth that would be capable of utilizing the resources available on Europa are the sulfur-dependent thermophilic bacteria among the Archaea. These could have evolved around hydrothermal vents at the interface

between Europa's silicate core and the bottom sediment layers of the overlying ocean As you can imagine, scientists would dearly love to send a spacecraft to the surface of Europa to search for signs of life. At the moment such missions are only at the conceptual stage.

3.3 Summary of Section 3

There are two questions pertinent to the issue of life within the Solar System beyond the Earth:

- Are there places where life may once have evolved, but for whatever reasons did not survive?
- Are there examples of life elsewhere in the Solar System today?

The answer to these questions is that scientists simply do not know. Many planetary scientists would argue that on the balance of probabilities, the answer to both questions is 'no'.

'Life', within the context of Section 3, is confined to entities such as bacteria (prokaryotes) since it is known from our experience of life on Earth that they are both widespread and have a primitive ancestry. Should life have got started anywhere beyond the Earth, then, irrespective of the extent to which it may have evolved, it should have at least passed through the bacterial stage. Thus, our search for life in the Solar System is essentially a search for environments capable of supporting bacteria.

For the development of life on any particular Solar System body, including the Earth (as you saw in Section 2), the following three requirements need to be met:

- Presence of liquid water, to act as a solvent, and as a reactant
- Light, or chemical energy, to construct large molecules and enable other functions
- Supplies of the chemicals (atoms, ions or molecules) needed to construct living cells.

Most of the planets of the Solar System, i.e. Mercury, Venus, Jupiter, Saturn, Neptune, Uranus and Pluto, exhibit conditions that are, for one reason or another, considered unsuitable for life. In contrast, past or present environments on two bodies (namely Mars and Europa) are, at least in principle, capable of supporting life. A third body, Titan, could be in a state close to that required for the emergence of life.

Conditions on Mars in the past appear to be compatible with what is required for the development of life However, evidence for present life is very dubious. In 1976 two US spacecraft (*Viking 1* and 2) visited the planet with the goal of determining whether a martian biosphere exists today. A set of biological experiments gave results which, in isolation, could have been interpreted as indicating life. However, a second type of experiment showed there to be no organic materials present. Therefore, most scientists reject the idea of life at present on Mars. The positive results from the biology experiments are considered to have an alternative, non-biological explanation.

Recently, there have been some controversial findings from martian meteorites, which have been interpreted as showing fossilized biological remains in the samples. Supporting evidence comes from the presence of complex organic molecules (polycyclic aromatic hydrocarbons), small magnetite and sulfide grains, and low-temperature carbonates. The inference here is that life existed on Mars at some point early in the planet's history. Unfortunately, each line of evidence can be interpreted abiologically. So the question of life on Mars remains, as yet, unresolved. More will be learned about Mars when results from *Pathfinder* and subsequent missions are analysed.

Europa, a large satellite of Jupiter, is a body that has a generally smooth, icy crust with no craters, which suggests relatively recent internal activity (acting to remove

the evidence of impact events). Because the necessary measurements have not yet been made, a complete description of the interior of Europa is not available, and three different models can be invoked to explain the overall density of the body. The most likely model suggests a deep, extensive layer of liquid water beneath a surface layer of ice, the liquid water overlying a large silicate-rich core, which might still be warm enough to generate hot spots. The liquid water and hot spots would be a consequence of tidal and radiogenic heating

The overall composition of Europa might resemble that of the type II carbonaceous chondrites (primitive meteorites known to contain water and organic compounds). Laboratory studies of carbonaceous chondrites indicate that Europa would then be endowed with significant quantities of organic compounds. Conditions at the core–ocean interface on Europa may be analogous to those around hydrothermal vents on Earth. If so, it is possible that Europa could support/is supporting life. The continuation of the *Galileo* mission should provide data that will result in more complete, more reliable models of the interior of Europa.

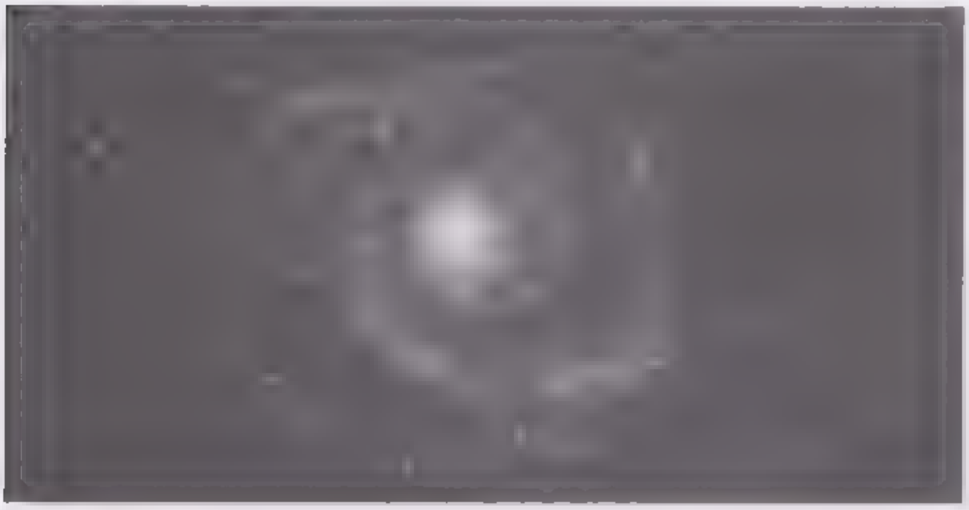
Life beyond the Solar System

4

We look now beyond the Solar System, and because the most likely place to find life is on the surface of a planet in orbit around a star (or on the surface of a satellite in orbit around such a planet), the first step is to find planets orbiting other stars — extrasolar planets. We shall look at how this has been attempted, and with what success. We shall then discuss how such extrasolar planets can be investigated for signs of life.

4.1 The search for extrasolar planets

At present, instrumental limitations confine astronomers to the nearer regions of our Galaxy in their search for extrasolar planets. In Block 3, Section 3.2, you learned that there are about 10^{11} stars in the Galaxy, and that they are arranged in space in the manner of Figure 4.1



(a)

(b)

Figure 4.1 Two schematic views of our Galaxy: (a) face view, and (b) edge view. The disc is about 40 000 parsecs (pc) across and about 600 pc thick. The position of the Sun is described in the text. 1 pc = 3.09×10^{16} m (a more approximate value of 3×10^{16} m was used in Block 11)

Where is the Sun in Figure 4.1?

The Sun is in the Galactic disc, about half way from the Galactic centre to the edge of the disc

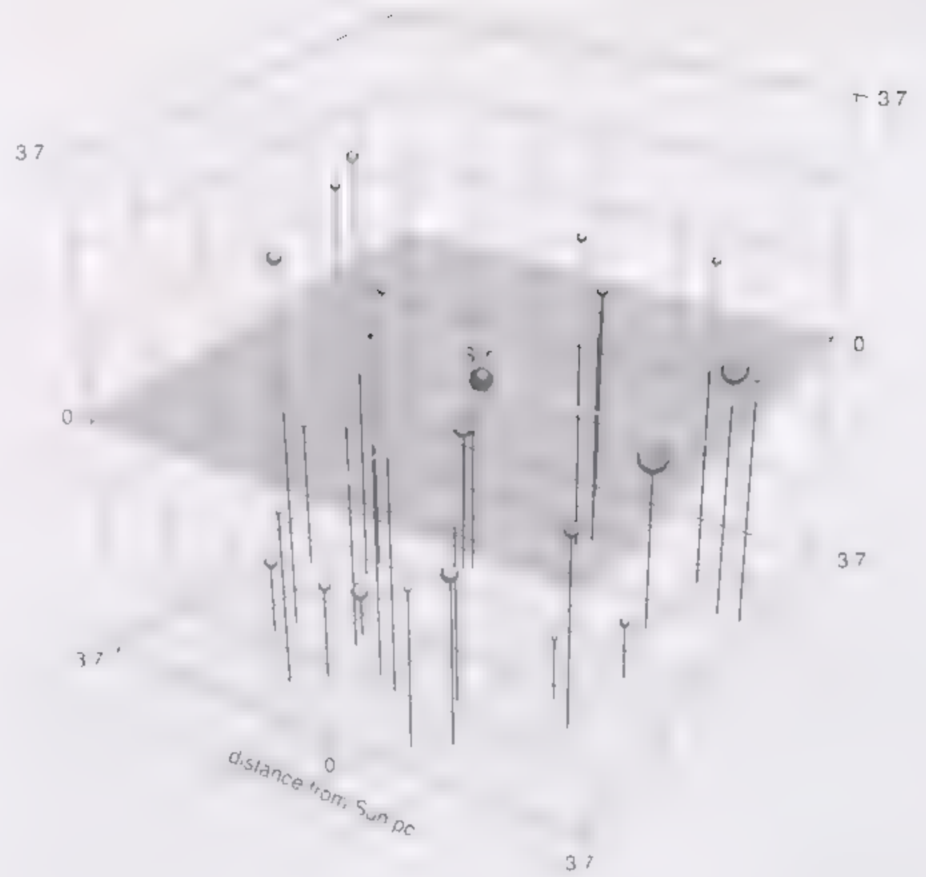
The Sun, being in the disc, is thus in a region of the Galaxy that is relatively well populated with stars. Figure 4.2 (*overleaf*) shows, on a larger scale, our immediate stellar neighbourhood, where the spacings between the stars are on average a few parsecs (about 3.09×10^{16} m), abbreviated to pc. If you read Block 11 you may recall that the derivation of a parsec was explained in Box 2.1. Spacings of a few parsecs are fairly typical of a much larger region around the Sun. There are something like 2 000 stars within 30 pc of the Sun, and about 50 000 within 100 pc

What is 100 pc in kilometres?

1 pc = 3.09×10^{16} m = 3.09×10^{13} km

So 100 pc = $100 \times 3.09 \times 10^{13}$ km = 3.09×10^{15} km

Figure 4.2 The stellar neighbourhood of the Sun, showing the 25 nearest stars. Note that the term 'star' includes systems of two or three stars in orbits around each other. The sizes of the spheres representing the stars increase as the luminosity increases.



Though 100 pc is a long way by terrestrial standards, it is a short distance by cosmic standards, and modern techniques of planet detection could certainly hope to find any planets around stars within 100 pc of the Sun, perhaps further. Therefore, there are already many tens of thousands of stars that are targets for investigation.

When we think about detecting planets, the method that probably springs to mind is direct imaging, in which the planet is seen as a point of light separate from its star. There is, however, a grave problem with this method that can be illustrated if you consider a pinhead held a few metres from a powerful streetlight at night. From a range of several kilometres, the light reflected by the pinhead would be drowned by the powerful light we receive directly from the streetlight. The situation for stars and planets is just as bad. For example, if we were looking at the Solar System from a distance of only 10 pc, the solar radiation reflected even by the giant planet Jupiter would be entirely drowned by the direct solar radiation received by our detectors. As a result, the only techniques that have so far (2002) revealed extrasolar planets are indirect: the existence of planets has been inferred from their effects on the motion of the stars that they are orbiting.

4.1.1 Detection of planets from stellar motions

Recall from Block 3, Section 4, that the planets in our Solar System are held in their orbits by the gravitational force that the Sun exerts on them. Gravity is a universal force. Therefore the planets exert a gravitational force on the Sun. Moreover, the magnitude of the gravitational force that the Sun exerts on a planet is the same as the magnitude of the gravitational force that the planet exerts on the Sun. For example, if the gravitational force that the Sun exerts on Jupiter has a magnitude F_J, then the magnitude of the gravitational force that Jupiter exerts on the Sun is also F_J. (This is an aspect of Newton's third law of motion, briefly alluded to in Block 3, Section 4.) Thus the Sun must be accelerated by Jupiter. The outcome is that as Jupiter orbits the Sun, the Sun goes around an orbit of its own. However, the acceleration of the Sun is small.

From Newton's second law of motion (Block 3, Section 4), obtain an expression for the magnitude of the acceleration a_S of the Sun in terms of F_J and the Sun's mass m_S.

Newton's second law of motion states that, for any mass m:

$$F = ma \tag{4.1}$$

Thus, applying this to the case in hand:

$$F_J = m_S a_S$$

and so:

$$a_S = \frac{F_J}{m_S} \tag{4.2}$$

Likewise, the acceleration of Jupiter is:

$$a_J = \frac{F_J}{m_J} \tag{4.3}$$

From Equations 4.2 and 4.3:

$$\frac{a_S}{a_J} = \frac{(F_J / m_S)}{(F_J / m_J)}$$

$$= \frac{F_J}{m_S} \times \frac{m_J}{F_J}$$

Therefore:

$$\frac{a_S}{a_J} = \frac{m_J}{m_S} \tag{4.4}$$

But the mass of the Sun is about 1 000 times greater than the mass of Jupiter, so Equation 4.4 shows that a_S is about 1 000 times less than a_J. What is the consequence for the size of the Sun's orbit?

To answer this question it helps to imagine a planetary system consisting of a star with a mass m_{star}, and a single planet with a mass m_{planet} that is as much as 0.2 times the stellar mass (20%). Let us also suppose that the planetary orbit is circular. In this case the orbits of the star and planet are as shown in Figure 4.3 (*overleaf*). The planet moves in a circular orbit around a point on a line between the two bodies, and the star goes around the same point also in a circular orbit. Note that the orbital periods of both bodies around this point are the same, and that this is also the orbital period of the planet as seen from the star. From Newton's laws it turns out that the ratio of the orbital radii, r_{star}/r_{planet}, is the same as the ratio of the accelerations:

$$\frac{r_{star}}{r_{planet}} = \frac{a_{star}}{a_{planet}} \tag{4.5}$$

For the system in Figure 4.3, what should the ratio r_{star}/r_{planet} be drawn as?

By applying Equations 4.4 and 4.5 to this system:

$$\frac{r_{star}}{r_{planet}} = \frac{a_{star}}{a_{planet}} = \frac{m_{planet}}{m_{star}} = 0.2$$

Therefore, r_{star}/r_{planet} should be 0.2.

You can measure Figure 4.3 to see if it has been drawn accurately.

Figure 4.3 A star with a planet with a mass that is 20% of the star's mass — a greatly exaggerated planetary mass. The orbits are circular and presented face on to us

The point around which both bodies move is called the **centre of mass** of the system. You can get a feel for the centre of mass by imagining (or building!) a model of the system in Figure 4.3, with two balls connected by a thin lightweight rod. The centre of mass is the point on the rod where the balls and stick balance, and do not tip over one way or the other. Not unreasonably, the balance point is nearer the more massive ball. You can also simulate the orbital motion. If you were to push a pin at right angles through the rod at the point of balance, and rotate the system around the pin, then this is how the star and planet orbit the centre of mass.

We have just established a general result, which we can express compactly as an equation:

$$\frac{r_{star}}{r_{planet}} = \frac{m_{planet}}{m_{star}} \tag{4.6}$$

Thus, for the Sun, if Jupiter were the only planet in the Solar System, the radius of the Sun's orbit would be about 1 000 times less than that the 7.8×10^8 km radius of Jupiter's orbit. The presence of the other planets complicates the picture, but because Jupiter is the most massive planet by some margin, the outcome is not greatly changed. The average radius of the Sun's orbit is thus only about 10^6 km, about the same as the Sun's radius. Nevertheless, observers with our technology on planets around nearby stars could detect the orbital motion of the Sun and hence deduce the existence of the more massive planets in the Solar System.

The stars are copious sources of radiation, and this enables us to measure their positions and motions very accurately. In practice, there are two main techniques for detecting stellar orbital motion, and we shall describe them now.

4.1.2 The astrometric technique: the measurement of stellar positions

Figure 4.3 shows a stellar orbit presented face on to us. Suppose that the orbital period is 5 years, and that the centre of mass in this system is stationary with respect to stars that are so distant that they constitute an apparently fixed background. Therefore, over a period of 5 years, the star will move around a circular orbit with respect to the stellar background, as in Figure 4.4. By measuring the position of the star for several years, its orbital motion can be detected, and the existence of the planet inferred. This is the basis of the **astrometric technique**: the detection of planets by measuring the position of a star at various points in the star's orbit.

Figure 4.4 A nearby star moving in a circular orbit with respect to an apparently fixed background of more distant stars.

To see what sort of information about the planet we can get from astrometry, it is useful to rearrange Equation 4.6 so that the mass m_{planet} is the subject.

- Perform this rearrangement.

- One way is to swap the equation left to right, and multiply both sides by m_{star}. The result is:

$$m_{planet} = m_{star}\left(\frac{r_{star}}{r_{planet}}\right) \tag{4.7}$$

To obtain m_{planet} we thus need to know the three quantities on the right-hand side of Equation 4.7. Observations of the stellar position give us r_{star}, provided that we know the distance to the star. This distance can be obtained by measuring the parallax angle, ψ (*psi*, pronounced 'p-sigh').If you studied Block 11 then you may recall from Box 2.1 that if the same part of the sky is observed at intervals of several months of time, nearby stars will be seen to exhibit very small shifts from one interval to the next. This phenomenom is known as *parallax*. The *parallax angle* (ψ) is defined as *half* the angular shift of the star, as measured from positions in the Earth's orbit, six months apart. Parallax is illustrated in Figure 2.1 in Block 11. r (in pc) = $1/\psi$ (in arc seconds), so if the angle is 1 arc second then the star is 1 pc away; if the angle is 0.1 arc second then the star is 10 pc away, and so on. Observations of the star itself allow astronomers to estimate its luminosity (power emitted) and surface temperature. Its mass m_{star} is then roughly the same as that of stars of similar luminosity and temperature whose masses have been obtained by independent methods. The value of r_{planet} is calculated from the measured orbital period of the star, plus the measured values of r_{star} and the estimated value of m_{star} The details will not concern us. The important point is that with the three quantities on the right-hand side of Equation 4.7 known, m_{planet} can be calculated. The astrometric technique thus gives us the mass of a planet and the radius of its orbit. Its orbital period is the same as that of the star (Section 4.1.1), so we get that too.

In reality there are two complications. First, in addition to the orbital motion in Figure 4.4, there is also a steady motion of the whole system with respect to the Solar System. This is due to the different velocities through space of the centre of mass of the Solar System and of the other system. Fortunately, the orbital motion can be separated from the steady motion. Second, if there is more than one planet with sufficient mass to make an observable contribution to the star's motion, then the orbital motion of the star is more complicated, though the individual contributions can be separated out. Note that to establish the existence of a planet we must observe the star for an appreciable fraction of the orbital period. In the Solar System the orbital period of Jupiter is nearly twelve years, so it can take some time to build up data on stellar positions that would reveal any planetary system.

Question 4.1 A planet is in orbit around a star that has a mass about 0.8 times that of the Sun. It has been established that, as measured from the centre of mass of the system, the radius of the star's orbit is 2×10^6 km, and the radius of the planet's orbit is 3×10^8 km.

(a) Given that the mass of the Sun is $1.989\,1 \times 10^{30}$ kg, calculate the mass of the planet.

(b) Given that the mass of the Earth is 5.974×10^{24} kg, calculate by what factor the mass of this planet exceeds the mass of the Earth. ◀

4.1.3 The radial velocity technique: the measurement of stellar velocities

Suppose that the system in Figure 4.3 were presented edgewise to us, so that our viewpoint was along the page, rather than perpendicular to it. In this case, instead of a circular path in the sky, the star would appear to move from side to side across the sky. The astrometric technique can still be used to reveal the masses and orbits of the planets. However, a second technique is now available. This is possible because the star is moving towards us during half its orbit, and away from us during the other half, i.e. it has a variable speed in the radial direction, a variable radial velocity. This motion can be detected because of the Doppler effect (Block 11, Section 2.2).

- What is the Doppler effect?

- In the Doppler effect, there is a change in the wavelength of the radiation received from a source, when the source is in motion with respect to the observer.

When the star is moving towards us, its spectral lines are shifted to shorter wavelengths (blue-shifted), and when it is moving away from us its spectral lines are shifted to longer wavelengths (red-shifted). By detecting these shifts we can infer the presence of the planet. Figure 4.5 shows the spectral shifts at various points in the edgewise orbit.

The oscillating Doppler shift arising from the orbital motion of the star will be superimposed on the Doppler shift arising from the steady motion of the whole system towards or away from us. However, the two contributions are readily distinguished, the oscillation appearing as a periodic variation in the steady shift. The amplitude of this oscillation is called the Doppler amplitude, and it is proportional to the mass of the planet.

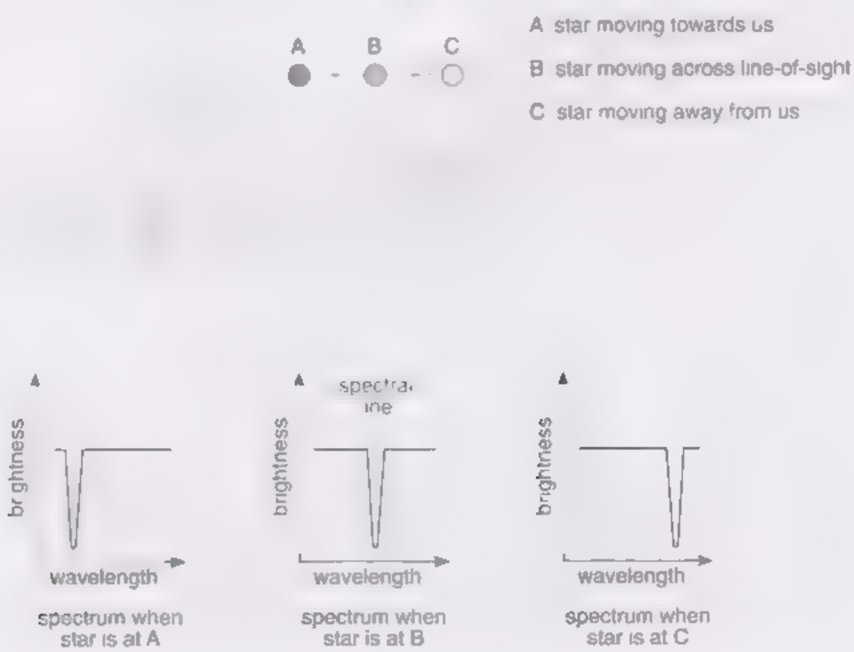


Figure 4.5 An edgewise view of the orbital motion of a star with respect to an apparently fixed background of more distant stars, plus the corresponding Doppler effect on the wavelength of a line in the star's spectrum

This **radial velocity technique** is capable of detecting planets at greater ranges than the astrometric technique. Provided that the star is bright enough to have readily visible spectral lines, then it does not matter how far away it is — there is no diminution with distance in the size of the wavelength changes. By contrast, in the astrometric technique, the greater the range from which we view the orbit in Figure 4.4, the smaller the star's orbit will appear on the sky.

There is, however, a disadvantage with the radial velocity technique. For a given system, if the orbit is presented face on, as in Figure 4.4, then the star does not move towards and away from us in its orbital motion, and so there are no oscillating Doppler shifts — the Doppler amplitude is zero. At the other extreme, the case in Figure 4.5, the variation in radial velocity is a maximum, and so we get the maximum Doppler amplitude for this particular system. If the system were presented at some intermediate angle then we would get an intermediate Doppler amplitude. This introduces an ambiguity, as follows. Imagine that we observe a system and measure a certain Doppler amplitude. We do not know the angle at which we are seeing the system. If we assume it is near to edge-on then we would deduce a certain mass m_{edge} for the planet. If, in fact, the system is not near edge-on then, to produce the same Doppler amplitude, the planet must have a mass greater than m_0 – this is because only a proportion of the star's motion is now along the radial direction. The radial velocity technique does not reveal the angle of view, and so the planetary mass we obtain from this technique is the minimum value $m_{edge-on}$ – it could be greater. It is the actual mass only if the system is presented edge-on.

A rough estimate of the angle of view can be obtained from the way that the rotation of the star modifies its spectral lines, as you will see in Activity 4.2. The important point is that we can do rather better in many cases than merely obtaining a lower limit to the planet's mass.

The occultation technique

There are some other indirect techniques for detecting planets, but we'll mention only one. You can discover it for yourself by examining Figure 4.5.

- If our view is exactly edge-on, or very nearly so, what event, once per orbit, could reveal the existence of the planet?

- The planet will pass between us and the star, resulting in a small decrease of the power in the starlight.

This is the occultation technique — the planet occults ('hides') part of the star. It requires a very good chance alignment of the planet's orbital plane with our line of sight, and so this method can reveal only a very small fraction of planetary systems.

Activity 4.1 Changing radial speed of a star

Table 4.1 lists the radial speed [illegible]

Table 4.1 The [illegible]

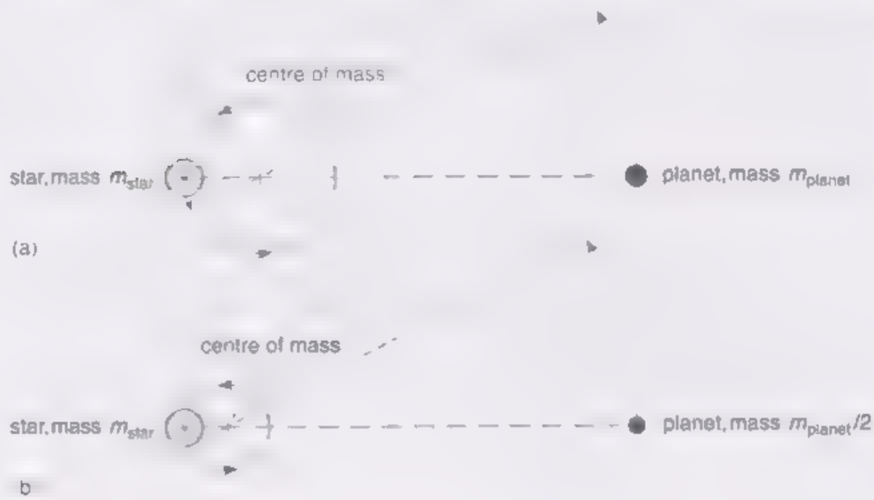
time/day	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
v/km s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
time/day	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
v/km s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

4.1.4 The easiest types of planet to detect

Before you read on, spend a moment thinking about what sort of planet, in terms of its mass and its orbit, would be the easiest to detect with the astrometric and radial velocity techniques.

For both the astrometric technique and the radial velocity technique, the greater the mass of the planet the greater the effect on its star, and so the easier it is to detect. Consider the two systems in Figure 4.6, and suppose that they are at the same distance from the Earth, and that the mass of the star, and the separation between the planet and the star, are the same in both cases. The systems differ in that in (a) the planet is 0.2 times the mass of the star, whereas in (b) it is 0.1 times the stellar mass.

Figure 4.6 Two planetary systems, which differ only in that the mass of the planet in system (a) is twice that in system (b)



What is the ratio r_{star}/r_{planet} of the orbital radii in each system?

From Equation 4.6, the ratio is 0.2 in system (a), in which the planet is 0.2 times the mass of the star, and 0.1 in system (b).

Because the star–planet separation is the same in both cases, you can see from Figure 4.6 that the larger stellar orbit is in the system with the larger mass planet. *The larger the stellar orbit the easier it is to measure with the astrometric technique. This is also the case for the radial velocity technique. This is because the orbital periods in Figure 4.6 are determined by the total mass of the* system. Therefore, because the star accounts for nearly all of this mass in each system, the times it takes the stars to get around their orbits are not very different. This means that the star with the larger orbit has to move faster. Consequently, the greater the mass of the planet the greater the variation in Doppler shift of the stellar spectral lines.

Consider now the two systems in Figure 4.7, in which the masses of the stars are again the same, but now so too are the masses of the planets. The systems differ in the distance between the star and its planet. The centre of mass is again located in accord with Equation 4.6. Therefore, *the greater the star–planet distance, the greater the radius of the star's orbit, and the easier it is to measure with the astrometric technique.*

With regard to the radial velocity technique, the outcome is less obvious. On the one hand, the smaller the star–planet distance, the smaller the radius r_{star} of the star's orbit, but on the other hand it turns out that the star's orbital period P is also smaller. The speed of the star in its orbit is proportional to r_{star}/P, but with r_{star} and P both reduced, it is not obvious which effect 'wins'. It turns out that P is more reduced than r_{star}, and so the orbital speed is greater for smaller star–planet distances. Consequently, the larger variations in Doppler shift of the stellar spectral lines occur with the smaller orbits. Therefore, *the smaller the planetary orbit the easier it is to detect the planet with the radial velocity technique.* The reduced orbital period of the star also carries the additional advantage that a complete orbit is observed in a shorter time.

Figure 4.7 Two planetary systems, which differ only in that the distance between the star and the planet in system (a) is twice that in system (b).

Question 4.2 Imagine two as yet undiscovered planetary systems, in each of which a planet with the same mass as Jupiter is in orbit around a solar-mass star. Table 4.2 lists other properties of these systems. For each system discuss whether the astrometric technique or the radial velocity technique is the more likely to detect the system, or whether there is little to choose between the two techniques. ◀

Table 4.2 Some properties of imaginary planetary systems in which a Jupiter-mass planet is in orbit around a solar-mass star.

System	Distance of system/pc	Star–planet distance /Jupiter–Sun distance*	Angle of view
A	10	10	nearly face-on
B	1 000	0.1	nearly edge-on

*The Jupiter–Sun distance is 7.8×10^8 km, or 2.5×10^{-5} pc.

4.1.5 Results from the stellar motion techniques

We turn now to the results from the indirect techniques. Up to 1995, this would have been a very short account indeed! Then the situation changed dramatically.

9

Activity 4.2 The planet of 51 Pegasi

You should spend no more than about 20 minutes on this activity.

[illegible]

Article 9 'The planet of 51 Pegasi' describes the discovery of one of the first extrasolar planets. The article was published in January 1996, a few months after the discovery was announced, and is from *Sky & Telescope*, a magazine pitched at a level appropriate for amateur astronomers. The article was written by Alan MacRobert, an associate editor of *Sky & Telescope*, and by the magazine's technical editor Joshua Roth.

There are several terms and concepts in the article with which you might not be familiar, but these should not prevent you from getting a lot out of this article. None of the terms merits inclusion in the *Course Glossary*, and none is included in Objective 1.

After you have read the article, you will be asked to tackle Questions 4.2.1–4.2.3, so you should have a quick look through these now so that you can make notes that will help you to answer them.

You should now read Article 9.

Question 4.2.1 (a) List points of similarity and a point of difference between the 51 Pegasi system and the Solar System.

(b) How could the difference have arisen? ◀

Question 4.2.2 [illegible] ◀

Question 4.2.3 [illegible] ◀

Since 1995, many other planetary systems have been discovered. By July 2002, 101 planets had been confirmed, distributed over 88 planetary systems. Of these, 11 are multiple systems – two triple-planet systems, the rest doubles. For the up-to-date position see http://www.obspm.fr/encycl/encycl.html.

Figure 4.8a shows the number of planets with masses $m_{\text{edge-on}}$ lying within various mass ranges, i.e. the mass distribution of the 101 planets. The mass unit is the mass m_J of Jupiter, 318 times the mass of the Earth and the most massive planet in the Solar System (Block 3, Section 5.2.1, Table 5.1). The minimum mass $m_{\text{edge-on}}$ is used for each exoplanet because (up to July 2002) all of them have been discovered by the radial velocity technique, and only in a few cases are there reliable estimates of the angle of view. You can see that the smaller the mass range the greater the number of planets in it, with the greatest number of exoplanets in the range 0–1 m_J. However, as yet there are no planets known anywhere near the Earth's mass – the smallest $m_{\text{edge-on}}$ so far is 0.12 m_J, which is 38 times the mass of the Earth.

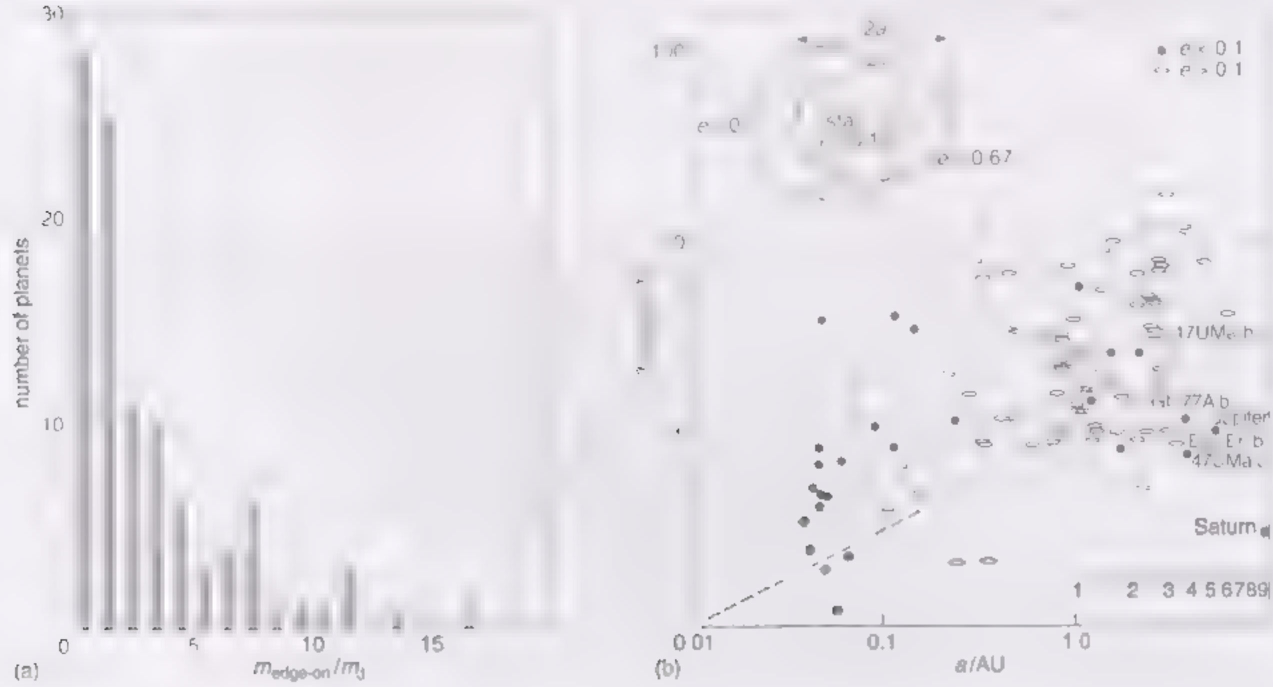


Figure 4.8 (a) The mass distribution of the first 101 planets discovered. (b) The semimajor axes of the orbits of the 101 planets in astronomical units AU (1 AU is the average distance between the Earth and the Sun). *Inset*: elliptical orbits with various eccentricities.

- Assuming that there are Earth-mass planets in some of the systems, why has none yet been discovered?

- The lower the mass of the planet the less its effect on its star, so low-mass planets are discriminated against.

Earth-mass planets are presently beyond detection by the radial velocity technique, and also by the astrometric technique. They are detectable by the occultation (transit) technique if the star is small and if the orbit is (almost) edge-on.

The question arises of whether all the true masses are considerably greater than $m_{\text{edge-on}}$, as would be the case if all the orbits were nearer face-on than edge-on. This is extremely unlikely – if the orientation of the orbits is random then it can be shown that the vast majority of planets will have masses less than a factor of two greater than m. So, the masses$_{\text{edge-on}}$ of these planets are predominantly of the order of the mass of Jupiter.

But are they also like Jupiter in composition, dominated by the light elements hydrogen and helium, and therefore unsuitable for life (Section 3.1.2)? We can answer this question if we know their radii. An Earth-like planet will have a composition dominated by the heavy elements that constitute rocks, and will be smaller than a hydrogen–helium planet of the same mass. The radius of a planet can be obtained by the occultation technique, and many of the exoplanetary systems have been scrutinized in this way. So far, just one planet has been observed to occult its star, the star HD209458. This shows that the planet is a bit bigger than Jupiter with an actual mass (we are seeing the orbit edge-on) of 0.69 m . This certainly rules out a rocky-iron composition and shows that this planet is much more like Jupiter than Earth in composition. There are in any case great difficulties in understanding how any circumstellar disc (Section 4.1.6) could have contained enough heavy elements to make hundreds of Earth masses of rock and iron. There is a consensus that all the planets so far discovered are more like the giant planets in our Solar System than they are like the Earth.

Though the exosystems contain 'Jupiters', nearly all of them have orbits very different from that of Jupiter. Figure 4.8b shows the sizes of the orbits, as measured by the semimajor axes a. A planet's orbit is an ellipse, as shown in the inset to Figure 4.8b. An ellipse can be more or less elongated, and the semimajor axis is half of its elongated dimension (inset). Elongation is measured by the eccentricity e of the ellipse. If the eccentricity is zero there is no elongation and an ellipse becomes a circle of radius a. In Figure 4.8b the elongated symbol shows those orbits where the eccentricity exceeds 0.1, which is one of the cases in the inset.

The eccentricity of Jupiter's orbit is only 0.048. By contrast, many of the exoplanets have highly eccentric orbits, particularly those not so close to their star. Equally remarkable, most of the exoplanets have far smaller orbits than that of Jupiter, which has a semimajor axis of 5.2 AU. In comparing orbits, note that the scales in Figure 4.8b have unequal increments, as you can see from the values on the axes and from the detailed scale at lower right. This is a 'powers-of-ten' scale, an example of a logarithmic scale, which facilitates the graphing of values that cover a wide range. You have met such scales before, in Block 3 Section 7.4.2 in the Richter scale of earthquakes, and in Block 8 Section 9.2 in the pH scale.

Estimate the semimajor axis of the smallest orbit in Figure 4.8b.

The smallest orbit has an a value of about 0.03 AU.

These innermost giants are therefore about 30 times closer to the star than the Earth, at 1 AU, is to the Sun. Any 'Jupiter' closer to its star than 1-2 AU could not have formed there – the circumstellar disc is too hot and too sparse. Instead, the planet must have formed farther out and then interacted with the remnants of the circumstellar disc so that it migrated inwards.

As yet, no exoplanet has been observed in a large, low-eccentricity orbit like that of Jupiter. Is the Solar System a freak? Probably not. Giant planets close to the star are the easiest to detect by the radial velocity technique (Section 4.1.4) Therefore, there could be many systems not that different from the Solar System awaiting discovery. Moreover, among many of the systems already discovered, it is possible that Earth-like planets could survive at just the right distance from the star for them to be habitable. The range of right distances is called the **habitable zone** of the star, and for the Sun it is centred on 1 AU (the Earth's distance from the Sun).

Question 4.3(a) What consequences might the migration of a giant planet have for the formation or survival of Earth-like planets in the habitable zone of a star? ◀

(b) Once migration has ceased, what is required for the subsequent formation of Earth-like planets in the habitable zone? ◀

So far, a few thousand nearby stars have been investigated, with a concentration in the searches on solar-type stars. A few percent are known to have planets, and this number will surely grow as the more difficult discoveries of giants in large orbits are made. That planetary systems might indeed be common, and therefore potential habitats too, is indicated by the presence of circumstellar discs around many stars.

4.1.6 Circumstellar discs

It is thought that the planets in the Solar System originated from a disc of gas and dust around the young Sun (Block 3, Section 5). If this is right, and if planetary systems are common, then many young stars today should have such discs — and indeed they do. The first was discovered in 1983, around the star Beta Pictoris. An image of this disc is shown in Figure 4.9. It is presented almost edge-on, and is visible through the light from its star that it scatters. Detailed studies have revealed that the disc has a hollow centre, like a doughnut. Distortion of the disc at the edge of the hollow indicates the presence of planets within the hollow.

By the time the 51 Pegasi system was discovered in 1995, many more circumstellar discs around young stars were known, and Figure 4.10 shows two of them. This image was made by the Hubble Space Telescope at visible wavelengths. It reveals what seem to be discs of dust and gas surrounding two newly formed stars. These fuzzy blobs could be infant solar systems in the making. Discs can also be imaged at longwave infrared wavelengths, through the infrared radiation that the dust particles emit

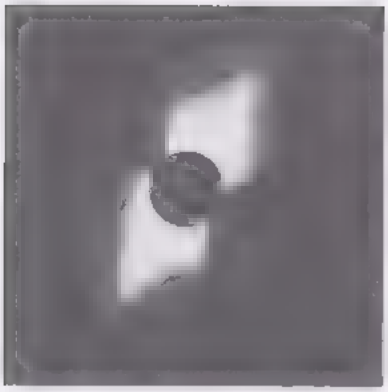


Figure 4.9 The dust disc around the star Beta Pictoris, seen at visible wavelengths via the light it scatters from its star. The disc is presented nearly edge-on Beta Pictoris is obscured to enable the disc to be seen

- What would have to happen to the temperature of the dust for it to emit sufficient *visible* radiation to be detected?

- The dust temperature would have to be higher (Block 2, Section 5)

At even longer wavelengths — radio wavelengths — we can detect spectral lines emitted by the molecules of the *gas* in the discs, and more discs have been discovered this way. It is clear that the majority of young stars have discs of dust and gas around them. Thus, with an abundance of discs from which it is believed planetary systems form, it is likely that planetary systems themselves are common.

With all the indirect evidence indicating that planetary systems are not rare, perhaps common, astronomers are being inspired to great efforts to obtain images of extrasolar planets. Though such imaging is not yet feasible, what are the prospects for the near future?

Figure 4.10 Two circumstellar discs in the Orion Nebula, about 500 parsecs from Earth, imaged by the Hubble Space Telescope, the dust being seen at visible wavelengths

4.1.7 Imaging of planets

We have already noted a major obstacle to obtaining images of planets.

- What is it?

- The light reflected by the planet is feeble compared with the light of its star, and the two bodies appear to be so close together from our distant vantage point that the starlight overwhelms the light from the planet.

To see how best to overcome this obstacle you need to know something of how telescopes work.

Large astronomical telescopes are **reflecting telescopes** — they collect light by means of a large dish-shaped mirror, as in Figure 4.11. The mirror forms an image by focusing light via the secondary mirror onto the image plane, where a detector can be placed to record the image. The mirror acts like the big lens at the front of a pair of binoculars, or like a camera lens. For large telescopes, mirrors are preferred to lenses because they are cheaper and give better quality images. You can demonstrate that a dish-shaped mirror forms an image if you have a mirror that magnifies you when you look into it (such as some shaving mirrors or some make-up mirrors). Direct the mirror at a window a few metres away, and place a piece of paper in front of the mirror, as in Figure 4.12. Move the paper forwards and backwards and you will find a position where you obtain a sharp image of the window.

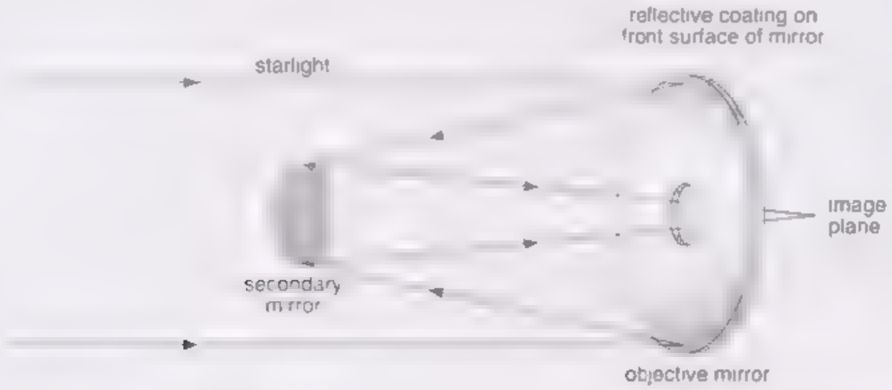


Figure 4.11 A telescope that uses a mirror to form an image — a reflecting telescope

For reasons which are beyond the scope of this block to explain, the amount of detail in the image is limited by the size of the mirror. All we need to note here is that the larger the mirror (or lens) the finer the detail in the image. In other words, there is a degree of blurring in the image, and the larger the mirror the smaller the degree of blurring. A star is so far away that the telescope 'should' produce an image that is little more than a point. In reality it produces a much larger image, a blurred disc. The blurred disc is brightest in its centre and gradually fades towards the edges, as in Figure 4.13a. The top part of the figure is an impression of what the image might look like, and the graph beneath it is the variation in brightness along a line across the centre of the image. Any planet will also be imaged as a blurred disc of the same diameter as the image of the star, though far fainter. Thus, as Figure 4.13a shows, the image of the star overwhelms the image of the planet. However, if the mirror were sufficiently large, the images of star and planet would disentangle, as in Figure 4.13b, and the planet would be seen.

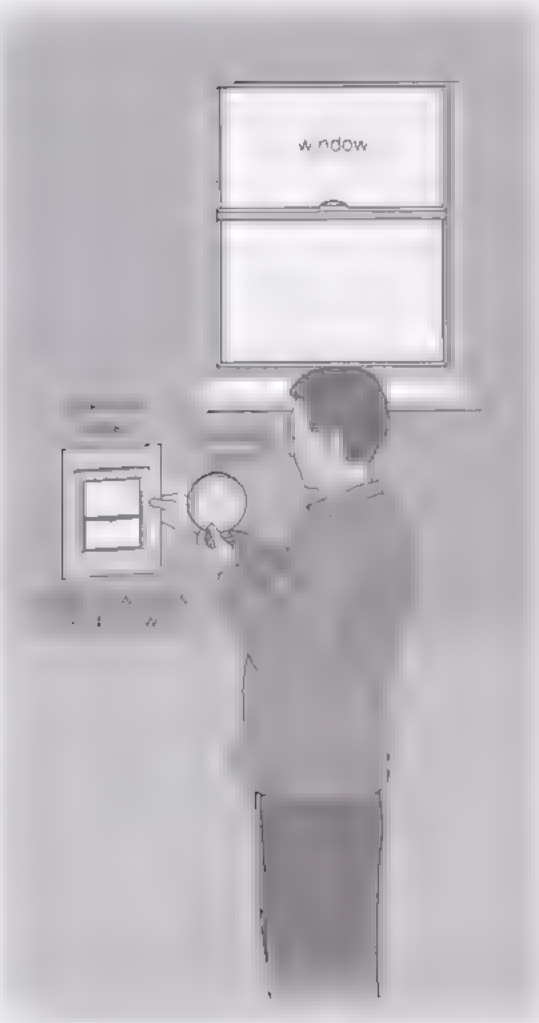


Figure 4.12 Forming an image with a mirror that magnifies.

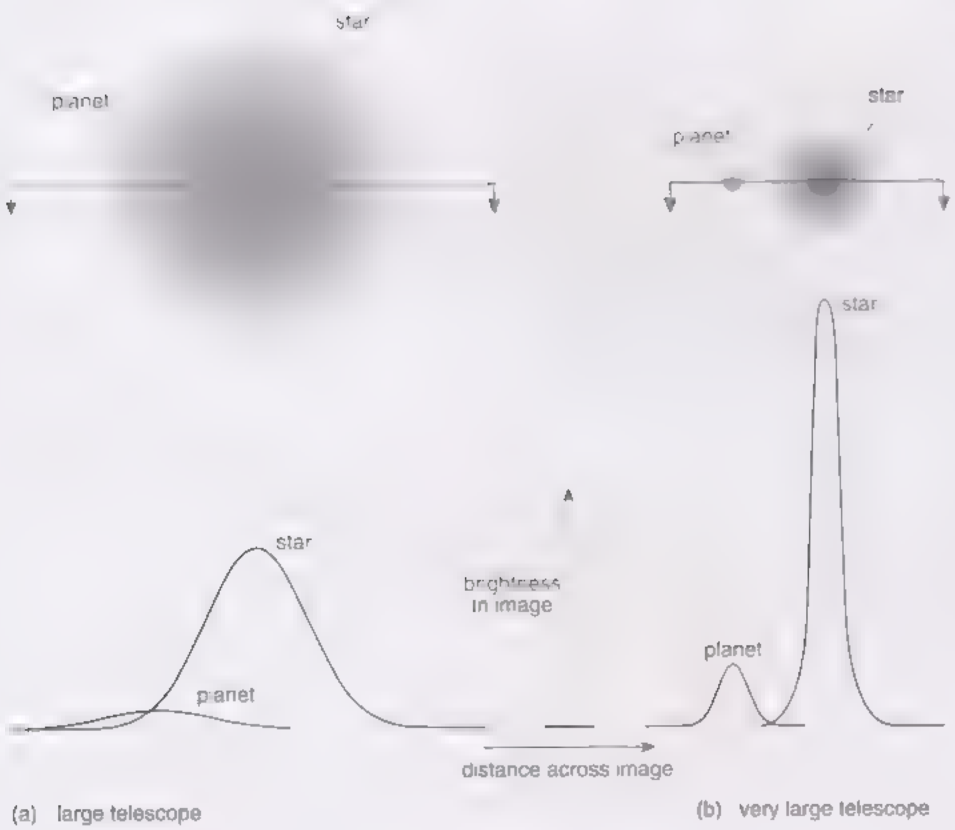


Figure 4.13 Illustrative light distributions across the images of a star and its planet produced by (a) a large telescope, (b) a very large telescope

Note that in Figure 4.13 the difference in brightness between the star and the planet has been greatly underplayed. In reality the planet is far, far fainter, particularly at visible wavelengths where we have light *emitted* by the star and starlight *reflected* by the planet. At infrared wavelengths things are not quite as bad, because we now have longwave infrared *emission* from the planet, and the longwave infrared emission from the star is in most cases much weaker than its visible emission. (For the Sun, you saw that this is the case in Block 2, Section 5.)

The largest telescopes today that work at visible or infrared wavelengths have huge mirrors about 10 metres in diameter. However, to obtain images of planets around nearby stars we need telescopes that are much larger even than this. Fortunately the crucial dimension is the distance of one edge of the mirror from another: there does not have to be mirror filling the whole area! Thus the single huge mirror in Figure 4.14a produces images with detail no finer than that from the array of smaller mirrors in Figure 4.14b. The downside is that the actual collecting area of the array is less, so longer exposures have to be used to collect enough light get a suitably bright image. It also takes many exposures with the mirrors in different orientations to build up the detail. In spite of this, and though highly sophisticated techniques are required to combine the images from the separate mirrors in an array, a telescope constructed from an array of small mirrors is much cheaper than a single mirror many metres in diameter. The array approach is called *interferometry*, a term you will meet in any further reading about this subject. Figure 4.15 shows the four largest telescopes in one array, the Very Large Telescope. See http://www.eso.org/ for the latest news.

Figure 4.14 (a) A single mirror 100 metres across. (b) An array of smaller mirrors that produces the same fine detail as the single mirror in (a). Note that the 10 m diameter mirrors in (b) are as large as the largest single mirrors today that work at visible or infrared wavelengths

Figure 4.15 The four large cylindrical buildings that house the four 8-metre diameter telescopes of the Very Large Telescope at the European Southern Observatory site in Cerro Paranal in Chile. In addition to these four large telescopes there will be a few smaller ones. Overall the array will give detail corresponding to a single mirror about 200 m across. Completion of the array is expected in around 2010.

Some large mirrors today are not single, but made up of segments fitted together. Examples are the two Keck telescopes on Mauna Kea. Each of these is 10 metres in diameter but made up of 36 hexagonal segments 1.8 metres across. The segments are kept in accurate positions by a sophisticated dynamic adjustment system at the back of each segment. By using many segments rather than a single mirror there is the cost advantage of mass production, and this makes it feasible to contemplate what are called Extremely Large Telescopes, or ELTs. One design under study is by the European Southern Observatory, and is called OWL, which can either be regarded as named for the eye of the Owl, or standing for OverWhelmingly Large telescope. OWL would have a segmented mirror 100 metres in diameter so could obtain images of planets around nearby stars. For the latest news on OWL see http://www.eso.org/

Highly sophisticated techniques are also used to overcome another problem — the image-blurring effect of the Earth's atmosphere. The atmosphere is not a perfectly homogeneous optical layer but varies in its optical properties as a result of small variations in density from place to place. The pattern of variation is constantly changing due to the winds, and the result is a blur that wobbles about, rather like the view of the bottom of a busy swimming pool from a vantage point above the surface. Atmospheric blurring prevents telescopes from giving the detail we expect from a mirror of given diameter. There are two ways of overcoming this problem. One is a recent technique called **adaptive optics**, in which the atmospheric motions are monitored, and appropriate compensating adjustments are made many thousands of times per second to the optical layout of the telescope.

What might be the other way of overcoming blurring due to the atmosphere?

The other solution is to place telescopes in space, above the atmosphere.

A space telescope is a better technical solution than adaptive optics, though for a telescope of a given size it is a *lot* more expensive. Therefore, in space an array of well-spaced small telescopes will be used to perform interferometry. There is an array under study by the European Space Agency called DARWIN (http://ast.star.rl.ac.uk/darwin/), and another by NASA, called Terrestrial Planet Finder (http://planetquest.jpl.nasa.gov/TPF/tpf_index.htm)

The current position is that the direct imaging of planets is not quite within our capabilities. However, astronomers know how to do it, and there is a good prospect that within the next two decades we shall have the first images of planets around other stars. As soon as we have such images, we shall be able to search the planets for biospheres. This search is described in Section 4.2

Question 4.4 (a) Consider the following two proposals, for telescopes to work at visible wavelengths.

System 1 A single mirror 20 m diameter, at ground level, and employing adaptive optics.

System 2 An array of 4 mirrors in space, each mirror being 1 m in diameter, and separated from its neighbours by 100 m.

(i) Why would each system be very expensive?

(ii) Which system would be less affected by the Earth's atmosphere?

(iii) Which system would give sharper images?

(b) What would be the advantage of working at longwave infrared wavelengths when trying to observe extrasolar planets?◀

4.2 The detection of life

Within a few decades, it is likely that the first image of an extrasolar planet will have been obtained. This will probably be no more than a fuzzy dot, at the limit of our instrumental capabilities. How shall we be able to tell if there is life on the planet? Travel to the planet, alas! will probably be out of the question, but there are a number of remote investigations that we could make.

4.2.1 Atmospheric spectroscopy

One of the most important investigations would be to establish whether any atmosphere existed, and if so, to establish its composition. This could be achieved by passing the radiation from the planet through a spectrometer and examining the spectral lines (Block 7, Section 2.1 and Block 11, Activity 2.2). The presence of certain absorption or emission lines would reveal that an atmosphere existed, and the wavelengths of the lines would indicate its composition. If water vapour were detected, and if further measurements showed that the surface temperatures and pressures fell within the range at which water exists as a liquid, then we could conclude that liquid water is present over some or all of the surface.

- Why would this be an exciting discovery in relation to extraterrestrial life?

- One of the necessary conditions for life as we know it, is liquid water (Sections 2.1.2, 2.4 and 3.1).

With the scientific belief that, given the right conditions for life, it is almost certain that life will emerge, we would feel optimistic that on that fuzzy dot a biosphere was present.

But could we be *certain* that life had actually emerged?

- From Blocks 2, 3 and 10, and from Section 2 of this block, state a global effect of the Earth's biosphere on the Earth's atmosphere.

- The oxygen in the Earth's atmosphere is almost entirely a product of photosynthesis, and is sustained by photosynthesis.

If we were to detect evidence of oxygen in abundance, then it would be *fairly likely* that there was an active biosphere: we know of no better way than photosynthesis of sustaining a substantial quantity of a highly reactive gas like oxygen in the atmosphere (see Task 1 of Activity 3.1). Oxygen would be easier to detect as ozone (O_3) rather than the form we breathe (O_2), but this would make no difference — detectable quantities of ozone require much greater quantities of O_2. If there were oxygen *and* evidence that liquid water was present, then this would make it *very* likely that there was an active biosphere.

Another important discovery would be of methane (Activity 3.1). A trace of methane and an abundance of oxygen would be a very strong indication of the existence of a biosphere. On Earth, the trace of methane is sustained largely through bacterial metabolism. Without such biospheric processes, the methane level would be far, far lower, because it is so readily oxidized by the oxygen.

It would thus be possible to detect a living biosphere. But the converse is not true. For example, if there were no oxygen we could *not* conclude that there was no biosphere.

- Has the Earth always had an oxygen-rich atmosphere?

- No. For most of Earth history the oxygen level was low (Section 2 and Block 10, Section 10.3).

The low level lasted throughout the first 2 000 Ma or so of the terrestrial biosphere. Throughout that enormous span of time the rate of oxygen production was insufficient to overcome the loss of oxygen through the oxidation of rocks, volcanic gases, and dead biomass. Only from about 2 000 Ma ago did the oxygen level in the atmosphere begin to rise.

Suppose though, that the evidence for a biosphere on an extrasolar planet was very strong. It would be tantalizing to come to this conclusion, but to be unable to find out much about it. Yet that is exactly the position we are likely to be in, unless, somehow, life can tell us about itself. One way in which this could happen is described in the next section.

4.2.2 The search for extraterrestrial intelligence (SETI)

Assume that there is an extrasolar planet on which an intelligent species has emerged, and that this species had developed and is using technology to attempt interstellar communication. In this case, if we detected and interpreted their signals, then the whole process of searching for planets and then investigating them would be short-circuited. We would at once know that there was life out there, and that it had become intelligent.

This is not just the stuff of science fiction. We have the capability of signalling across the Galaxy, and yet our technological civilization is very young. How much more capable might be older civilizations? Since 1959 astronomers have been searching the skies for signals, mainly by using radiotelescopes to search for radio signals, but now also by searching for visible light and infrared signals. This is an important aspect of **SETI** — the **Search for ExtraTerrestrial Intelligence**. So far (and in spite of the ever popular but misguided cover-up theories), no signals of unambiguously intelligent origin have been detected. But is this search a worthwhile activity, or a waste of time and money? What are the chances that there are other technological civilizations in the Universe with which we could communicate? Scientists disagree, as you will now discover.

10

Activity 4.3 The search for extraterrestrial intelligence: scientific quest or hopeful folly?

[illegible]

[illegible] Mayr [illegible] Harvard University [illegible] whether it is [illegible] from the Max [illegible]

[illegible] but not at [illegible] None of the [illegible] Objective [illegible]

[illegible]

[illegible]

Write a brief [illegible] words [illegible] which you [illegible] Mayr [illegible] more convincing [illegible] one sentence each.

[illegible] the arguments [illegible]

- Does an argument [illegible]?
- Does an argument [illegible] reasonable scientific expectation?
- Are exaggerated [illegible] or pessimistic claims being made?
- Are [illegible] scientific [illegible] prejudices creeping in, and [illegible] are these justified?

You will doubtless have come to your own conclusion about the likelihood of detecting extraterrestrial intelligence. It is difficult to predict the likelihood of success, given all the unknowns, though the lack of success so far indicates that civilizations attempting interstellar communication at radio wavelengths are at best rare in our region of the Galaxy. For the nearest stars we can also conclude that there are probably no civilizations that, like ours, leak radio communications into space without any deliberate attempt at interstellar communication. These leakages would probably be far more difficult to detect than the signals from deliberate attempts, which is why, so far, we can only exclude such civilizations for the nearest stars.

My own view (Barrie Jones, writing in mid 2002) is that the issue of extraterrestrial intelligence is such a huge and fascinating one that we should devote a small resource to searching. Fortunately, with recent developments in instrumentation and software it is possible to do a lot of searching on a shoestring. Moreover, dedicated amateur astronomers can make a contribution, and increasingly they are doing so. A small radiotelescope can be built using a large satellite dish, and the amateur can direct it to a few nearby stars for long periods in the hope that communication is intermittent, and thus missed so far by professional searchers. Amateurs can also direct modest optical telescopes to such stars, and look for laser signals. Success is not very likely, but the scientific reward for success would be huge.

On the question of life in general, rather than intelligence in particular, we already know that planetary systems are not rare, and few scientists disagree with the view that there is life elsewhere in the Galaxy, perhaps widespread. If so, then among the few thousand stars that we can see with the unaided eye, there might well be several orbited by a planet on which life has emerged. It is all the more exciting that we are within decades of having the capability of placing the issue beyond reasonable doubt.

4.3 Summary of Section 4

To discover life beyond the Solar System, the first step is to discover planets, and the second step is to investigate whether any of them support life. The discovery of planets would be bypassed through the discovery of signals from extraterrestrial intelligence, though there is considerable disagreement among scientists about the likelihood that technological civilizations exist beyond the Earth.

Over 100 extrasolar planetary systems had been discovered in the neighbourhood of the Solar System by mid-2002, and the number is growing monthly. These have been discovered indirectly, by the radial velocity technique. So far, all the planets are giants and some of them are in orbits that challenge our understanding of how planetary systems form. It is inferred that planetary systems with Earth-sized planets are not rare.

Evidence that planetary systems might be common is provided by the large proportion of young stars that are encircled by discs of gas and dust — discs that in many cases will surely be the birthplace of a planetary system, and in other cases provide evidence that a planetary system has already formed

Developments in instrumentation and techniques over the next few decades will make it possible to obtain images of planets. Once such images are obtained it will be possible to examine the radiation from planetary atmospheres for evidence of life. Suitable conditions for the emergence and sustenance of life would be indicated by the presence of water vapour in the atmosphere and by surface temperatures and pressures in the ranges that permit water to be liquid at the surface. If liquid water were present, then given our belief that, if the conditions for life are right, life will emerge, we would be optimistic that a biosphere was in place, particularly if oxygen was also present, though an absence of oxygen would not rule out life.

A very strong indication of an active biosphere would be the discovery of appreciable quantities of oxygen along with traces of methane, though the absence of these substances would not mean that a biosphere was also absent.

SA3

Activity 4.4 Extrasolar planets

(You should spend no more than 20 minutes on this activity.)

Introduction The third and final supplementary article (SA3) is 'Extrasolar planets' by Andrew Collier Cameron, and is from the January 2001 issue of Physics World. Though only about 50 exoplanets were known at that time the article is otherwise reasonably up to date. As with the other two supplementary articles, the end-of-course assessment (ECA) might be based in part on this article. You are to skim through some of this article in order to tackle Question 4.4.1. Do not try to understand every sentence but note only the topics covered. Skim SA3 now, omitting the sections 'Silicate clouds and the sodium greenhouse' and 'Tau Boo: now you see it, now you don't', and the first two paragraphs of 'Next steps'. Spend about 10 minutes on this.

Question 4.4.1 For the parts of SA3 that you skimmed, list four topics that have *not* been covered earlier in Section 4. *(About 20 words per topic should suffice.)* ◀

Summary of Block 12

The two big questions with which we began this block:

- How did life begin on Earth?
- Is there life elsewhere in the Universe?

have not been fully answered here. Nor would you find complete answers in any other text. We know little for certain about the origin of life on Earth, and though we have plausible theories about many of the stages, some other stages are very obscure. The transition from molecules to cells is perhaps the greatest mystery, especially the nature of the genetic material that carried information to organize the system. Suggesting that RNA was used before DNA is only a partial solution, because RNA is still a very complex molecule. Perhaps simpler molecules carried information before RNA. There is little prospect for much progress in the near future, perhaps not for decades, unless we discover unequivocal evidence of life or fossils beyond the Earth: such discoveries would provide valuable extra data.

The question of whether there is life elsewhere in the Universe could in principle be resolved tomorrow if intelligent signals were to be detected (or if extraterrestrials were to pay us a call!). Within the Solar System, forthcoming space missions should soon show whether there is life today on Mars, or whether there are fossils from a long-gone martian biosphere.

Beyond the Solar System, the observational evidence that planetary systems are not rare, perhaps common, plus the scientific belief that life will emerge whenever the conditions are right, means that even among the few thousand stars visible to the unaided eye, there might be a few planetary companions with life. The next few decades should yield a crop of Earth-sized extrasolar planets, and the subsequent investigations of their atmospheres might reveal incontrovertible evidence for life. Whether intelligent species have emerged in any of those biospheres will be far less certain.

6

Science discovered

You have now reached the final section of the final block of this course, and if you look back over the twelve blocks you will appreciate that a vast area of science has been covered. We started in Block 1 with a familiar topic, water — a topic that is closely related to your everyday experience — and we have ended by exploring topics that are at the forefront of current research, where scientists are still asking fundamental questions about the origin of the Universe and the origin of life. Along the way you will have developed your understanding of the way that the natural world works and of the ways in which scientists find out about how it works.

Discovering Science is an unusual course in many respects, and one of these is the way that it brings together the different disciplines of science. From the start of the course we were keen to show you how different disciplines could each contribute to the investigation of various scientific topics. Thus Earth science, physics, chemistry and biology have all played their part in our understanding of global warming, and equally they all have a part to play in answering the question 'Is there life elsewhere in the Universe?'.

We have also been keen to avoid delineating the different disciplines too clearly. In real life, science is a continuum, and is not rigidly compartmentalized. The boundaries between chemistry and biology are very blurred when it comes to topics such as enzyme chemistry and understanding the action of drugs at the cellular level. Similarly the boundaries between Earth science and physics become very blurred when we are considering radioactive decay processes in the Earth, radiometric dating and the behaviour of seismic waves. These fuzzy boundaries are also apparent in the transitions between some of the blocks in this course. Thus we moved naturally from what chemistry tells us about atoms, into the world of quantum physics, energy levels and spectra, and then moved back to look at what the electron structure of atoms tells us about chemical properties and chemical periodicity. And though the later blocks of the course are not seamlessly linked, biological evolution led us naturally into the study of the fossil record and the history of the Earth, which in turn led to the study of the history of the Universe from the time of the Big Bang. All of these aspects of evolution and history are reflected in the final block, and the quest to discover life elsewhere in the Universe.

We hope that studying *Discovering Science* has whetted your appetite to learn more about science! One of the characteristics of scientists is that they ask, and answer, questions, and generally the more answers that they come up with, the more questions they are spurred to ask. One of the important ideas that we have tried to convey is that science is not a cut and dried subject. It is dynamic, alive and developing. At various stages in human history people have pronounced that all important science had been discovered, but this has never proved to be the case. There are still important questions that scientists are investigating — How will the Earth's climate react to increasing CO_2 levels? Can we design drugs to combat AIDS? How can we explain the periodic mass extinctions of life? Is the fate of the Universe to expand forever or to collapse back in on itself? Is there life elsewhere in the Universe?

But stepping back from the questions that research scientists are attempting to answer, we hope that studying the course has set up all kinds of questions in your mind — that it has left you wanting to find out more about particular areas. There will undoubtedly have been some parts of the course that you found more exciting and interesting than others. These are likely to be the parts about which you have lots of questions that you want to find answers to, and you can discover some of these answers by studying more advanced science courses in the appropriate area.

And, finally, as well as meeting a wide variety of science, you have also developed and improved many skills. These skills will be of use to you in future courses and in other areas of your life. To identify some of the skills developed, we suggest that you try the final activity of the course.

Activity 6.1

As you have studied S103, you will have developed and enhanced a number of skills. These have undoubtedly proved useful to you during the course, and we hope that they will or already have proved useful in other parts of your life. For convenience, the Course Team grouped the skills developed in this course into four categories when listing them in the Block objectives: science skills, communicating science skills, mathematical skills and effective learning skills.

For each of these categories, name two or three skills which you have developed while studying S103 and which you have found particularly useful, and note down an example of an occasion when you used each skill. You may find it helpful to think of the things that you can do now that you would not have been able to do, or not do so well, when you started the course. You may also wish to add some comments about why you have found the skill useful and/or advice to yourself about further use or development of the skill.

When you have produced your list, read the comments on this activity, which include a summary of the main skills that the course has aimed to develop.

Questions: answers and comments

Question 3.1

The best way of summarizing the internal constitution of the giant planets is to draw a sketch, equivalent to the appropriate half of Figure 5.2 of Block 3, as in Figure 3.10.

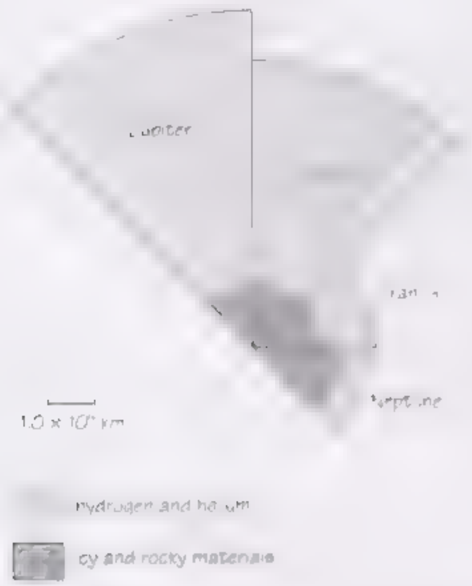


Figure 3.10 The internal constitution of the giant planets. Note that the boundaries are probably more fuzzy than shown here

Question 3.2

There is effectively a substrate upon which life could exist (i.e. dust particles). There is a reasonable temperature (about 0 °C). We are not sure about nutrients, but comets could replenish the atmosphere with vital components. And there is water, which could condense on the particles. So, at face value it would appear that life is at least possible. {But there is a serious problem for any aspiring life forms, which we have not considered in the text. Any dust particles would tend to move vertically up and down through the atmosphere. This has the effect that any individual particle would be subject to extreme variations in temperature, making the evolution or survival of life very unlikely.}

Question 3.3

In the 'cold start' hypothesis, life originated on Earth in oceans beneath a planet-wide ice shell. Hydrothermal vents could have enriched the oceans in substances important for life's origin, such as ammonia and methane. It is possible that the conditions under the ice shell of Europa have been, and are, similar to those that would have existed on an ice-covered Earth

Question 4.1

(a) From Equation 4.7, the mass of the planet is:

$$m_{\text{planet}} = (0.8 \times 1.9891 \times 10^{30}\,\text{kg}) \times \left(\frac{2 \times 10^{[illegible]}\,\text{km}}{3 \times 10^{[illegible]}\,\text{km}} \right)$$

$$= 1 \times 10^{28}\,\text{kg}$$

to one significant figure (the orbital radii are only known to one significant figure).

(b) The mass of this planet divided by the mass of the Earth is.

$$\left(\frac{1 \times 10^{28}\,\text{kg}}{5\,974 \times 10^{24}\,\text{kg}} \right)$$

which is 2 000 (to one significant figure). Thus the planet's mass is about 2 000 times the mass of the Earth. {This is about six times the mass of Jupiter.}

Question 4.2

{Remember that the stellar orbit will be a fraction of the size of the planetary orbit.}

System A

The nearly face-on view would make the Doppler variations very small. Moreover, the planet is not particularly close to the star and so, even edge-on, the Doppler variations would not be particularly large. By contrast, the system is only 10 pc away, and the star–planet distance is large, and so there would be a readily detected stellar orbit on the sky Thus the astrometric technique is the more likely to detect the planet's presence. {The orbital period, however, is *very* long, so it would take many years to build up sufficient positional data.}

System B

The radial velocity technique is the more likely detection method here. The nearly edge-on view maximizes the variation in the Doppler shifts, and these would be large because of the small star–planet separation. This same small separation makes the stellar orbit small, and the system is a long way off, and so the astrometric technique is disadvantaged. {If the system were *very* nearly edge-on then there might be occultations of the star by the planet.}

Question 4.3

(a) A giant planet migrating into or across the habitable zone would be likely either to remove any Earth-like planets that had already formed, or to scatter the smaller components from which such a planet might have been forming. [In fact the latter is more likely, because of the relatively long time it takes for the final stages of building an Earth-like planet. It

is also sufficient for the giant to approach the habitable zone — it need not enter it, because as it migrates, the changing gravitational forces it exerts on material in the habitable zone will be sufficient disturbance.]

(b) To form an Earth-like planet there must be sufficient rocky-iron material in the habitable zone. This must be able to come together to build an Earth mass, and therefore the giant must be in an orbit not too close to the habitable zone. [It is plausible that enough material will be left swirling about, and provided that the giant is not near the habitable zone it is plausible that an Earth-mass planet or two could form.]

Question 4.4

(a) (i) System 1 is expensive because it is a single mirror of enormous size, and System 2 is expensive because it is in space.

(ii) Though System 1 uses adaptive optics, this is not quite as good as getting above the Earth's atmosphere, as System 2 does, so System 2 is less affected by the Earth's atmosphere.

(iii) System 2 will give sharper images than System 1 because it has a larger overall size, though it will take longer to acquire the images.

(b) The advantage of working well into the infrared is that the ratio of brightness of the planet to the brightness of the star is greater than at visible wavelengths.

Comments on activities

Activity 1.1

Subsidiary questions that would help to construct a hypothesis about how life began on the Earth include the following:

- What is life?
- Does all life on Earth today seem to have had a common ancestor?
- What was the first form of life like?
- When did life begin?
- What were the conditions like on the Earth at that time?
- Did life, in fact, originate on Earth, or elsewhere?

{Do not worry if your list included only one or two of our items. Also, it is possible that you listed items that are *not* on our list. It is quite possible that these extra items are appropriate, though to make sure you should ask yourself whether they really would help to construct a hypothesis about life's origin.}

Activity 2.1

Question 2.1.1 The two types of fossil evidence are, first, bacteria-like cells (microfossils) and, second, stromatolites (Block 10, Section 2.3). The latter indicate that photosynthetic prokaryotes, either cyanobacteria (formerly known as blue–green algae) or organisms similar to purple or green photosynthetic bacteria (see Figure 21 in Article 1) were present 3 500 Ma ago.

Question 2.1.2 Isotope ratio data (the ratio of the two carbon isotopes ^{12}C and ^{13}C) in the Isua rocks from Greenland provide evidence for the presence of carbon derived from living systems. {There are further comments about these data in the updating comments in the text that follows this activity.}

Question 2.1.3 Comparisons of the sequence of bases in ribosomal RNA. The greater the number of sequence differences between two groups/species, the longer ago they had a common ancestor on the genealogical tree.

Question 2.1.4 The tree *itself* does not suggest any date for the origin of life. All it does is to indicate that three branches arose from a common ancestor early in the evolutionary process. Dated fossils show that photosynthetic bacteria existed 3 500 Ma ago. Therefore, the common ancestor of Eubacteria is older (Figure 21 in Article 1), and the time at which the Archaebacteria, Urkaryotes, and Eubacteria branched from the common ancestor must be earlier than 3 500 Ma ago. Therefore the origin of life was before 3 500 Ma ago.

Activity 2.2

Question 2.2.1 First, the rocks could be dated (using isotope analysis of argon and potassium as described in the box on p. 22 of Article 2; see also Block 10, Section 8.5). Second, knowing where on the Moon these rocks were collected, the number and size of craters in different regions allowed estimates to be made of the frequency and size of impacts at different dates. Comparisons with Mercury and the oldest parts of Mars showed that they had a similar history of cratering, i.e. the size–frequency graphs were similar to those of the Moon. For reasons explained on p. 21 of Article 2, there is no such historical record for Earth but if the Moon and Earth's neighbouring planets have a similar history, then, presumably, Earth too was subjected to a similar bombardment.

Question 2.2.2 Numerous observations and measurements show that comets consist largely of frozen water (p. 20 of Article 2), and comets would be expected to form some part of the population of bodies in the heavy bombardment of the Earth. *Assuming* that 10% of the bodies colliding with the early Earth were comets that comprised 50% water, Chyba suggests (p. 22) that they would have delivered 'an ocean's worth of water to the Earth's surface'. Note the 'assuming' here: there is no firm evidence that this happened. However, Chyba cites two types of evidence supporting this view: (a) there is indirect evidence that water existed on the early Mars and Venus, which might have been delivered by comets (but could also have originated in other ways); (b) the ratio of heavy hydrogen (deuterium, D) to ordinary hydrogen (H) in cometary ice and in the Earth's oceans is very similar and is higher than in volcanic water trapped inside the Earth when it formed. Chyba is careful to say that evidence (a) and (b) are *consistent* with his hypothesis about the origin of Earth's oceans but never says that they *prove* it.

{This is how good science is done and, by now, you should recognize it as an example of the scientific method: you have a hypothesis to explain something; you make predictions from that hypothesis (here, the predictions are that there would have been water on neighbouring planets and that the isotope ratios in the water of comets and the oceans would be similar); you test those predictions by experiment or observations; and finally you decide if your results match your predictions. If they do, they are consistent with the hypothesis; if they do not they are inconsistent and you need to re-think the hypothesis. Whatever the outcome, it will probably be necessary to make and test more predictions, have your results checked by other people and try very hard to find other explanations for your results, e.g. how *else* might the high D : H ratio in seawater be explained if not by a cometary origin?}

Question 2.2.3 The article suggests that organic molecules in comets might have been delivered intact to the Earth and might then have provided the starting material for chemical evolution that led to the origin of life. That comets contain organic molecules is beyond

reasonable doubt. That such molecules survived when comets collided with Earth is by no means certain. Moreover, comets would have contributed to 'impact frustration', and thus would have helped delay the origin of life. {Furthermore, and Article 2 does not discuss this point, it is not certain that, even if such molecules survived impact, they were present in sufficient *quantities* on the early Earth to have contributed significantly to chemical evolution.}

Activity 2.3

Question 2.3.1 The nub of Bada's argument in Article 3 is that there simply was not enough organic material arriving on Earth from space to have stocked the oceans: the prebiotic soup would have been too dilute. His evidence is based on measurements of an amino acid that is common on extraterrestrial bodies such as meteors or comets but rare on Earth. He looked for increased concentrations of this amino acid in the fall-out from known impacts (one in Siberia and one from an older impact 65 Ma ago) and in the ice of Antarctica and Greenland (which accumulate dust from space over thousands of years). There was very little of this amino acid present and even if he assumed that 10 000 times more impacts occurred on the early Earth, he argues that there would still have been too little material arriving from space.

Question 2.3.2 Bada suggests that chemical evolution, the reactions that provided the building blocks of living organisms, took place not in the atmosphere, which might have had an unfavourable chemical composition, but deep in the oceans, where the chemical precursor molecules were vented from the Earth's interior, particularly from hydrothermal vents, and could build up into a prebiotic broth of useful concentration. The surface of the oceans, he suggests, was frozen. Deep under the ice, water remained liquid at around −2 °C and organic syntheses occurred {especially around the hydrothermal vents}.

The crucial assumption of this hypothesis is that the early Earth was cold, with a GMST below 0 °C. Little evidence is presented to persuade readers that this was so, except for the lower solar luminosity, and Bada is really saying that *if* the Earth was cold, life could have appeared in this way. He further assumes that unfreezing of the oceans occurred because of a massive impact from space. Again there is no evidence for this idea but *something* would have had to happen to warm up the Earth: perhaps it was the heavy bombardment (Section 2.3.1).

Activity 2.4

Question 2.4.1 (a) Orgel and colleagues showed that by repeatedly adding (or feeding) low concentrations of monomers (or building blocks) to clay minerals, longer chains (longer oligomers) were formed than in the absence of clay. Nucleotide monomers formed nucleotide chains and amino acids formed amino acid chains (peptide chains). Thus solid mineral surfaces catalyse the formation of oligomers that are precursors of important macromolecules in cells

(b) The significance of these results is that they suggest how one problem in chemical evolution leading to the origin of life (hydrolysis of long chains) might have been avoided.

Activity 2.5

This activity gives you practice at comparing different sources of information and deciding whether they are actually saying the same thing (even if in different words or contexts) or saying something new.

(a) (i) The idea in SA1 that clay minerals could act as scaffolds, promoting reactions between monomers to form more complex molecules, was described in Article 4 (Orgel et al.).

(ii) The idea that rocks or minerals could also provide a special environment that protected reactants and products on the early Earth was mentioned in the text (top of p. 18) but is developed in more detail in SA1 (the container or protection idea).

(iii) The idea in SA1 that minerals could have jump-started critical chemical reactions, with iron sulfide (pyrite) possibly providing a source of energy, was touched on in the text (Section 2.4.1, second paragraph and Section 2.4.2, last paragraph). Similarly, the text mentioned (p. 20, second paragraph) that a template based on clay minerals might have been the first self-replicating system, preceding the RNA world, and SA1 also suggests that 'minerals may have jump-started the first self-replicating molecular systems' (p. 85)

(b) New ideas in SA1 are as follows.

(i) Crystals, such as calcite, selected particular forms of amino acids (left-handed (L) rather than right-handed (D) isomers) for the early reactions that led to the formation of self-replicating, protein-like molecules. [This could explain the otherwise puzzling fact that living organisms today use only L amino acids whereas D and L isomers are produced in equal amounts in organic syntheses.]

(ii) One of the critical reactions jump-started by minerals such as iron oxide could have been the reaction between hydrogen and nitrogen gas around hydrothermal vents to produce ammonia, a vital source of nitrogen for biological reactions (p. 83). This is a development from idea (iii) in (a).

(iii) Elements such as iron or sulfur made soluble and released from minerals (e.g. close to hydrothermal vents) could have become incorporated into organic molecules, which then acted as enzymes (the reactants idea, pp. 80 and 85)

Activity 2.6

Compare the plan that you produced with the plan below, which was produced by a member of the Course Team She has written the introduction and conclusion in full, but the plan for the main body of the account is in note form. Your plan is likely to be a lot less detailed and probably includes various abbreviations — it only needs to be intelligible to you, whereas the plan here needs to be intelligible to a large number of other people.

Introduction

From a scientific viewpoint (i.e. omitting divine intervention), there are only two ways in which life might have originated on Earth: by chemical evolution of life from simple chemicals, or by immigration of some form of life from an extraterrestrial source. Both of these mechanisms are described and compared in this account.

Chemical evolution

Paragraph 1: Chemical evolution — simple organic molecules evolved into more complex molecules from which, eventually, living cells were organized (Section 2.4); e.g. amino acids to proteins, sugars to complex carbohydrates, nucleotides to nucleic acids.

Great uncertainty about how process happened, many different hypotheses. Hypotheses based either on simulation experiments, e.g. Miller's experiments or similar (see Articles 2 and SA1, Section 2.4.1) or guessing state of the Earth when life is thought to have evolved and then predicting what sorts of chemical reactions could have occurred, e.g. 'cold start' (Article 3).

Paragraph 2: Origin of simple organic molecules on early Earth

- early hypothesis of Miller (generation in strongly reducing atmosphere by action of UV radiation) now regarded as unlikely.

Other hypotheses:

- origin at deep-sea hydrothermal vents, possibly when ocean surface frozen (Article 2);
- origin in shallow pools or at ocean surface (Section 2.4.1);
- origin on pyrite particles in the atmosphere (Section 2.4.1);
- origin at protected sites on/in rocks or minerals (SA1);
- simple organic molecules reached Earth from space via dust particles, comets or meteors (Article 2); Bada (Article 3) argues this was unlikely to be significant.

Paragraph 3: Origin of more complex organic molecules

- presumably in the same place(s) that simple molecules originated;
- problem of hydrolysis and need to maintain high concentrations of reactants (Section 2.4.1) led to suggestion that solid surfaces were important (Articles 4 and SA1)

Paragraph 4: Final stage: macromolecules to living cells

First cells probably autotrophic (Section 2.4.2). Must have had surrounding membrane — could have been important for conversion of external energy source into 'useful' energy (e.g. ATP) by proton pumping (Block 9). Also needed way to store and replicate information — possibly RNA, but simpler system could have operated in first cells, e.g. self-replicating protein-like molecules organized on a mineral template (Section 2.4.3 and SA1).

Extraterrestrial origin

Paragraph 5: Life, in some heat resistant form (e.g. spores or single cells protected by layer of carbon — Section 2.4) reached Earth on dust particles or interior of meteorites. Presumption that life arose by chemical evolution on another planet.

Comparison of hypotheses and their relative likelihood

Paragraph 6: Both hypotheses assume life originated by chemical evolution:

- chemical evolution hypothesis suggests it occurred on Earth;
- extraterrestrial hypothesis suggests it was on another planet.

Argument against chemical evolution on Earth — insufficient time between the Earth cooling down and earliest known life (Section 2.4).

Argument against ET origin — organisms unlikely to survive in space and during descent through Earth's atmosphere. No firm evidence that life exists or once existed anywhere else in Solar System.

Conclusion

In summary, it is generally accepted by most scientists that life must have originated by chemical evolution, but we cannot be sure whether this took place on Earth or whether life originated extraterrestrially. Recent speculation about the possibility of life having once existed on Mars provides some support for the extraterrestrial hypothesis. However, on the balance of evidence presented in Block 12, I think that the former alternative is most likely to be correct.

(Don't be worried if you found this activity difficult; extracting relevant information for an account like this, and particularly deciding which points to include and which to omit really is difficult. So when you compare your plan with the one above, you shouldn't be concerned if some of the points are different. The 800-word account you have planned would summarize a lot of information from Sections 2.4–2.4.3, and from Articles 2–4, so there is plenty of scope for different approaches. The most important aspects that you should have included are the two possible ways that

life might have originated — chemical evolution on Earth and immigration from elsewhere — with some explanation of each of them, together with a comparison of the two ways.

When writing an account in which the information comes mainly from OU texts, or from articles provided by the OU, you should not quote verbatim large sections. Make the points in your own words and then, in brackets, indicate where you got the information, e.g. (Section 2.4.1). Similarly, if you obtained information from non-OU textbooks, then give a reference to the books. The Appendix, on p.77, gives advice on how to do this.

Note that the end-of-course assessment will require you to produce an account that is based on some aspects of material in this block, and, if you haven't already done so, we recommend that you have a look at the ECA now. Then as you study the remainder of the block, you should highlight, or make notes about, any points that are relevant to the ECA, and this will help you when you come to produce your answer.}

Activity 3.1

Question 3.1.1 Silicon is unlikely to provide a good basis for life because it is far less able than carbon to form a variety of intricate compounds, including information-bearing molecules (in other words, there is no equivalent of DNA based on silicon). Also, silicon dioxide (the silicon equivalent of carbon dioxide) is a solid on planetary surfaces, not a gas; this would inhibit the development of a silicon-based metabolism

Question 3.1.2 Possible solvents are hydrogen fluoride (HF) or ammonia (NH_3). The former is considered unlikely because of the relatively low abundance of fluorine in the cosmos. Ammonia is a possibility, especially on a cold planet where water would exist only in the frozen state. {On the Earth ammonia freezes at −78 °C and boils at −33 °C.}

Task 1 Our summary is given below. You should compare it with yours, and if there is a wide difference, compare ours with the article.

1 In the observed electromagnetic radiation at near-infrared wavelengths there was a strong dip in brightness at 0.76 μm. This is due to absorption by molecular oxygen, implying that this molecule is abundant in the Earth's atmosphere. Photosynthesis is the only known process that could sustain such large quantities of O_2.

2 There was a sharp absorption of radiation with wavelengths of about 0.7 μm, which could not be attributed to any mineral species. Such a feature is not known from any other planet in the Solar System. This feature is due to chlorophyll, a green pigment found in plants that absorbs energy from sunlight, thereby enabling photosynthesis.

3 Within the infrared spectrum there was also a feature due to about 1 p.p.m. of methane. This is in extreme disequilibrium with all the oxygen present — without the constant addition of methane to the atmosphere (from bacterial metabolism) it would simply react with the oxygen to produce water and carbon dioxide.

4 One of the instruments picked up radio emissions that could not be explained by natural sources (such as lightning). The conclusion would have to be that the orderly signals were the product of a technological civilization. *(193 words)*

{Note that this is a summary of the *Galileo* search for life on Earth. It is *not* a summary of the whole article. You might find it useful to summarize particular aspects of the articles (after reading them), as practice for the end-of-course assessment.}

Activity 3.2

Question 3.2.1

Using laboratory simulations of lightning taking place in a model Titan atmosphere (originally using electrical spark discharges and subsequently using lasers), it is possible to produce a reddish sludge, which Carl Sagan has called 'tholin' (after the Greek word for mud). Sagan concluded that this material could be responsible for (a) the orange colour of Titan, and (b) the unusual way in which Titan reflects light. Within the atmosphere of Titan, tholins are thought to be formed by a complex interplay of photochemical processes. These processes start when ultraviolet light from the Sun interacts with a methane molecule (CH_4), splitting it apart to form various fragments known as radicals. Normally, one or two hydrogen atoms are produced, along with a corresponding radical composed of a carbon atom and three hydrogen atoms (i.e. CH_3), or one carbon atom with two hydrogen atoms (i.e. CH_2). Most of the hydrogen atoms recombine to form molecular hydrogen (i.e. H_2), whilst the carbon-bearing radicals interact to form various small organic molecules, the most abundant being ethane (C_2H_6). These types of reaction continue, eventually producing the more complex organic molecules known as tholins.

Question 3.2.2

Although the surface of the young Titan would have been covered with a layer of ammonia solution (i.e. ammonia in water), at the present day the surface is too cold for liquid water to exist. Thus, if left to its own devices, nothing much would happen on the surface of Titan other than the slow accumulation of tholins and any hydrocarbons raining out of the atmosphere. However, it is thought that when comets or meteorites impact the surface of Titan, the energy from the ensuing explosion not only excavates a crater (as on Earth), but also melts the target ice layers. Following large impacts, the melt (essentially a liquid ammonia solution) would take thousands of years to freeze again. Because the surface layers will also contain carbon in the form of tholins, hydrocarbons

and nitriles, there exists an environment on Titan where biological precursor molecules, such as amino acids, could be formed. Note that organic molecules could also be added to the mix from the impactor itself (comets are known to contain relatively large amounts of organic molecules, as are certain types of meteorite).

Activity 3.3

Question 3.3.1 1 In the presence of a small quantity of organic nutrients taken to Mars from Earth, gases were observed to exchange between martian surface samples and the local martian atmosphere.

2 After exposure of martian surface samples to organic foodstuffs, taken to Mars from Earth, the organic materials became oxidized.

3 Carbon dioxide was observed to be taken up by martian 'soils'.

Activity 3.4

Question 3.4.1 The five lines of evidence are given in the last paragraph (conclusion) of Article 6. They relate to the meteorite ALH84001, an igneous martian rock.

1 The rock was penetrated by a fluid along fractures and pore spaces, which then became the sites of secondary mineral formation and possible biogenic activity.

2 The carbonate globules at these sites have a formation age younger than that of the igneous rock.

3 Images of the globules and of other features show a resemblance to terrestrial micro-organisms, terrestrial biogenic carbonate structures, or microfossils.

4 There are magnetite and iron sulfide particles that could have resulted from oxidation and reduction reactions known to be important in terrestrial microbial systems.

5 At surfaces rich in carbonate globules there are polycyclic aromatic hydrocarbons.

Activity 3.5

Task 1 (a) Eleven of the twelve martian meteorites have young crystallization ages, and this rules out all parent bodies except Venus, the Moon, Earth, Mars, and some of the satellites of the giant planets. Venus is ruled out because rock fragments blasted from its surface would vaporize in the thick atmosphere. The satellites of the giants are ruled out because the fragments could not escape the gravitational field of the giant. The Earth and the Moon are ruled out because of the chemistry of the rocks. The martian meteorites are recognized as a group through their similar oxygen isotopic compositions, different from that of the Earth and the Moon. One of the group contains pockets of gases that have a similar composition to the atmosphere of Mars.

(b) Various features in the meteorite ALH84001 that have been interpreted as indicating that life once existed on Mars also have an abiogenic interpretation. The magnetite occurs as discrete grains, whereas biogenic magnetite occurs as a sequence of connected grains. The grains are also about 100 times smaller than those characteristic of terrestrial biogenic processes. They do not have the cavities observed in terrestrial microfossils, and cell-wall type structures have not been identified. The polycyclic aromatic hydrocarbons can be produced abiogenically.

Activity 3.6

Question 3.6.1 (i) The thin ice model In this model Europa is composed largely of hydrated silicates with a large core of dehydrated silicates (Figure 6-1 of Article 8), plus a very thin layer of water ice on the surface. The ice layer is of the order of a few km thick.

(ii) The thick ice model Here it is envisaged that internal heat has been sufficient to drive off the water from the hydrated silicates. This has left a larger core of dehydrated silicates overlain by a thick (about 100 km) surface layer of solid ice.

(iii) Ice–ocean model. This is similar to the thick ice model except that instead of solid ice at the surface there is a layer of liquid water (about 100 km thick) overlain by a thin layer (less than or equal to 10 km) of ice.

Activity 3.7

Question 3.7.1 Type II carbonaceous chondrites are about 2.5% by mass of carbon, and 13% by mass of water. Thus, an early bombardment of Earth by materials like carbonaceous chondrites would bring carbon and water to its surface. More importantly perhaps, the majority of the carbon in carbonaceous chondrites is in the form of organic compounds. Several biologically important classes of molecules are known to be included, including amino acids, purines and pyrimidines.

Question 3.7.2 The absolute quantity of soluble organics on Europa (2.4×10^{19} kg) is more than 10^4 times higher than the total amount of organics in the Earth's active biosphere (the total terrestrial biomass amounts to about 10^{15} kg — Block 2, Section 8.4.1). A concentration of 1% organics in water is sufficiently high to lead to abiotic chemical synthesis under favourable conditions. Clearly there could exist on Europa a chemical environment that has all the right hallmarks for one in which life could evolve. As yet, however, we do not have any evidence for life on the satellite.

Activity 3.8

There are no comments on this activity.

Activity 4.1

(a) A graph of the data is shown in Figure 4.16.

(b) The graph shows that there might be a planet orbiting this star because the radial speed seems to be

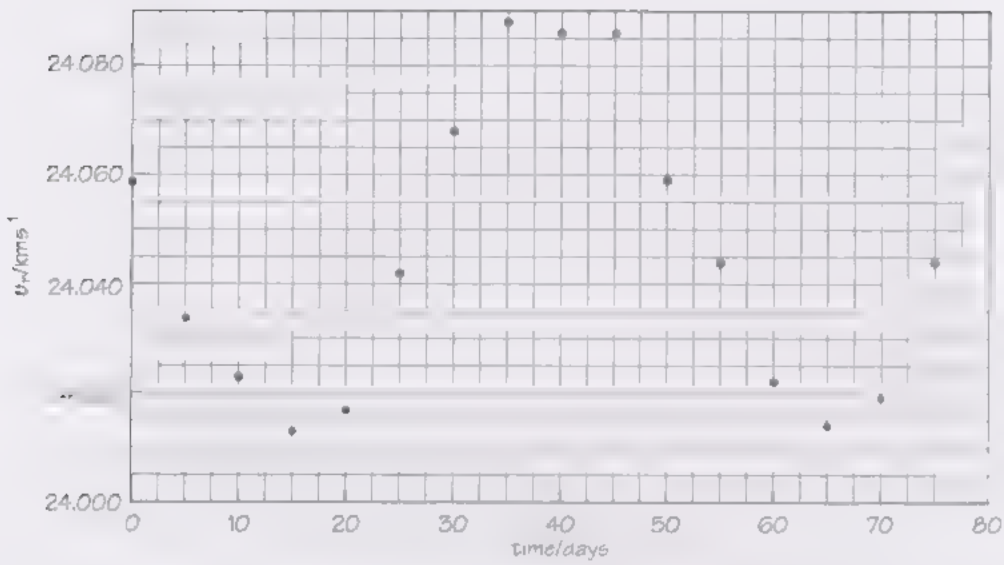


Figure 4.16 The radial velocity of a certain star.

varying periodically. {The graph is slightly irregular because the measurements have a degree of uncertainty.}

(c) The orbital period is about 50 days, with an uncertainty of about ±1 day {values up to ±2.5 days — the interval corresponding to the grid spacing — are acceptable}.

Activity 4.2

Question 4.2.1 (a) *Points of similarity* 51 Pegasi is a star similar to the Sun.

51 Pegasi has at least one giant planet in orbit around it

The planet's orbit is nearly circular.

Points of difference The giant is very close to 51 Pegasi.

(b) Theories of planetary formation show that it is unlikely that the planet of 51 Pegasi formed so close to its star from the coalescence of small bodies (in the normal planetary way). It might have formed as a separate condensation in the gas cloud that collapsed to form 51 Pegasi, or it might have formed in the normal planetary way further out, and spiralled in, or was flung inwards through a collision with another massive body.

Question 4.2.2 (a) The planet around 51 Pegasi is massive and in a small orbit. Therefore it gives rise to Doppler shifts that vary rapidly over a wide range of values. It is not a good candidate for the astrometric technique because the stellar orbit is small.

(b) Article 9 (p. 39) quotes Marcy and Butler's measurement for the semiamplitude of the radial speed of 51 Pegasi as $51 \pm 2\,\mathrm{m\,s^{-1}}$. This means that the range of variation is $102\,\mathrm{m\,s^{-1}}$, which is $\frac{102\,\mathrm{m\,s^{-1}}}{31.3\,\mathrm{m\,s^{-1}}}$ times the UK motorway speed limit, i.e. 3.3 times (to an appropriate number of significant figures). {This range of variation is only a small fraction of the mean radial speed of 51 Pegasi.}

Question 4.2.3 (a) Figure 4.17 shows a rotating star. The motion of the star along our line of sight has a maximum speed at one edge, and a minimum at the diametrically opposite edge, with intermediate values in between. This gives rise to a continuously varying Doppler shift in the light from across the diameter of the star, and hence to the broadening of the spectral line as shown.

(b) From the breadth of the spectral lines of 51 Pegasi, astronomers can calculate some fraction of the star's rotation speed, which is equal to the actual rotation speed only if the equator of the star is presented edge-on. The rotation speed can be estimated independently,

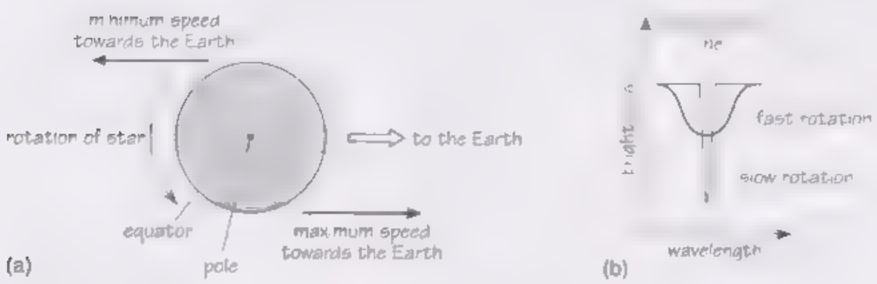


Figure 4.17 (a) A rotating star. (b) The Doppler broadening of a spectral line from the star.

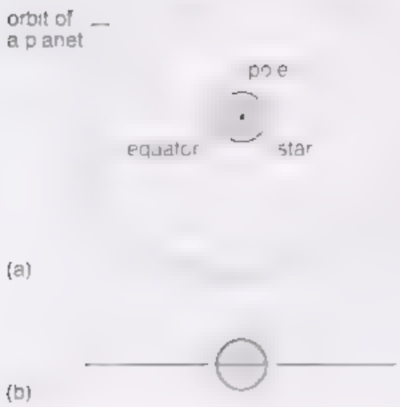


Figure 4.18 Two views of a planetary orbit in the equatorial plane of a star. (a) The 'pole-on' view. (b) The edge-on view.

and this estimate is not very different from the value obtained from the Doppler broadening. Therefore, the equator of the star is probably viewed not far from edge-on. The plane of the orbit of the planet is probably not far from the equatorial plane of the star, and therefore we are probably seeing the planetary orbit not far from edge-on (Figure 4.18b) Therefore, the lower limit on the planetary mass that the radial velocity technique yields is probably not very different from the actual mass.

Activity 4.3

Task 1 There is no 'right' response to this task. One possible response is below. You should compare it with yours to:

- check that the statements of Mayr's conclusion, and Sagan's conclusion, are broadly the same as yours;
- note the attempts made to justify the conclusions in a rational way, drawing evidence from the article (and elsewhere).

Mayr's conclusion is that the probability of extraterrestrial intelligence existing in our Galaxy is so low that it is a waste of effort to search for it. Sagan's conclusion is that the probability is sufficiently high to warrant searches. I found Sagan's conclusion the more convincing

Mayr's arguments are unconvincing because they rest on the specific case of the Earth's biosphere. He argues that the following steps are improbable:

- the emergence of intelligence;
- the emergence from intelligent life of a technological civilization that attempts interstellar communication in a form we could notice;
- that the civilization will send signals for a long time.

Yet the first two of these have already happened on Earth, and we have no idea for how long we would send signals if we decided to do so. Also, there are billions of years more that the Earth's biosphere could survive, perhaps with the evolution of far more intelligent species than ours.

In looking beyond the Earth, millions of biospheres are likely to exist in our Galaxy (both authors agree on this). Sagan believes that once a biosphere has become established, there would be strong evolutionary pressures on most planets towards the evolution of high intelligence. On many planets, natural selection would also favour the emergence of technical civilizations. Because civilizations will emerge at different rates, and because many stars are much older than the Sun, Sagan thinks it is likely that there are civilizations technically far more advanced than ours. I find this too optimistic. On the other hand he concludes that the chance of receiving a recognizable communication from ETI is far from negligible, and this seems reasonable to me.

I think it is impossible to conclude that intelligence is unlikely or likely. We simply don't know — we have to search for extraterrestrial intelligence to resolve the issue.

{Here is a possible alternative answer, based on *Mayr's* conclusions being found the more convincing.}

Mayr's arguments are very convincing, in particular that the following steps are improbable:

- the emergence of intelligence;
- the emergence from intelligent life of a technological civilization that attempts interstellar communication in a form we could notice;
- that the civilization will send signals for a long time.

On Earth it could easily have been the case that technological intelligence never emerged. Also, we could only have been deliberately sending signals into space for a few decades, and there's no reason to suppose that we shall do so in future continuously for hundreds or thousands of years — it would be dangerous to attract the attention of an aggressive species, unlikely though this is!

Finally, if these are millions of ETIs out there, why haven't we been visited? This seems to indicate that there aren't any ETIs.

{If you made the argument in the last sentence, you will have come up with your own version of what is called Fermi's paradox, named after an early exponent, the Italian–US physicist Enrico Fermi (1901 1954). This is the paradox. If extraterrestrial intelligence is

common, then it is very probable that many technological civilizations have existed for long enough to colonize the Galaxy. The fact that we have not been colonized is a powerful indication that there are no other technological civilizations in the Galaxy.

As with many things in SETI, there are counter-arguments, such as the 'zoo' hypothesis, in which it is supposed that ETIs don't interfere with primitive emerging technological civilizations such as ours. Most astronomers find the Fermi paradox intriguing, but inconclusive.}

Activity 4.4

Any *four* of the following will do.

- Ways in which planets can migrate inwards (or outwards) – 'Reflex orbit'.
- 'Top-down' and 'bottom-up' models of forming giant planets – 'Reflex orbit'.
- 'Free floating' planets, either formed free of a star or ejected from a planetary system – 'Reflex orbit'.
- The thermal evolution of 'hot Jupiters', slowing their shrinkage rate – 'Hints from other worlds'.
- Detection of planets through the gravitational bending of light – 'Next steps'.

Activity 6.1

We asked you to identify just two or three skills from each of the four categories, and you will have made your own individual selection, with your own personal examples to illustrate them. But thinking about your response should have increased your awareness of the range of skills you have developed while studying S103.

Identifying your skills in the way suggested in this activity would be particularly useful if you wanted to convince an employer that you were the right person for a particular job. In such a situation it would be useful to identify relevant skills and to explain how you would use them if you were offered that particular job. Providing examples of how and where you have developed and used skills would make your assertion that you had those skills much more convincing. This activity is a starting point for such an analysis, and you could continue with it at any time in the future.

While you have been studying *Discovering Science*, we hope you have mastered many of the following skills:

Science skills

Skills associated with practical work (designing and planning an experiment, making observations and measurements, recording and analysing results, assessing uncertainties, reaching a conclusion, looking critically at an experiment and suggesting improvements, etc.)

Modelling (using and/or devising for yourself simplified representations of some aspect of the world to help you to understand it)

Classifying (categorizing items according to their similarities and differences)

Using the scientific method (thinking about data, interpreting it, formulating a hypothesis, explaining results by referring to a hypothesis, deciding when further information is needed, gathering evidence to support/test/refute a hypothesis, judging between good and bad evidence, modifying a hypothesis, justifying a point of view, constructing an argument, showing how a conclusion was reached, being aware of assumptions, making assumptions, speculating, making predictions, problem-solving)

Communicating science skills

Understanding and using diagrams, graphs and tables

Using symbols (to represent physical quantities, or chemical elements and compounds)

Producing written accounts (of various lengths, for various purposes, for various audiences)

Mathematical skills

Arithmetic (do calculations — both on paper and with a calculator — involving positive and negative numbers, decimals, fractions, powers of ten, scientific notation, ratios and percentages, square roots, proportionality and inverse proportionality)

Algebra (use symbols in algebraic equations, and combine, rearrange and solve equations)

Graphs (plot data as a graph, work out gradient and intercept of straight-line graph)

Handling data (calculate the mean of a set of data, estimate uncertainties in data, quote data and answers to calculations to an appropriate number of significant figures by rounding)

Areas and volumes (for rectangles, circles, blocks and spheres)

Angles and trigonometry (use angles in degrees; sine, cosine and tangent calculations)

Effective learning skills

Setting objectives (analysing your learning needs and working out how to achieve them)

Planning and managing time and resources

Developing study skills (reading actively, taking notes for a variety of different purposes, producing summaries, distinguishing between information that you 'need to know' and information that it is 'nice to know', knowing when to seek help from other resources, knowing when to move on, learning about your own preferred ways of learning, making use of feedback, moving from specific to general and back again, relating new information and methods to what you know already, using analogies and classification systems)

Managing difficulties (both foreseen and unforeseen, learning difficult concepts, integrating study into a busy life, coping with the unexpected, keeping yourself motivated)

Reflecting on your performance (becoming aware of the processes you use, analysing your methods, generalizing, testing your skills in new situations, taking responsibility for improving your skills)

Criticizing and evaluating (your own work and that of others, and hence improving your performance)

Of course, we have aimed to develop skills that are useful to a scientist. However, there are many skills that cross subject boundaries, and although you may have developed them within the context of a science course, you will use them in a variety of different contexts. In particular, as you have studied *Discovering Science*, you have had an experience of learning which has equipped to undertake any new learning you choose in the future. Examples of the general skills you have developed include the ability to:

- *analyse*; you have analysed diagrams, maps, graphs, organic molecules, articles, course text, etc. as you have studied the course;
- *synthesize*; you have used this skill whenever you located material from a variety of sources, and put it together to develop your understanding of a topic, to write an account of a topic, etc.;
- *enquire*; we have encouraged you to formulate questions, perhaps only mentally, and to search for the answers, e.g. in designing experiments, in answering TMA questions, in trying to understand difficult concepts, etc.;
- *solve problems*; you developed this skill in the context of energy-related problems, and may have used it more generally in other areas of science, and also in dealing with time management, understanding difficult concepts, etc.;
- *work with precision*; this means not only that you are careful about the units you use and the number of significant figures you work with, but also that you use terminology accurately and appropriately;
- *cross-check results*, by asking yourself: 'Is this reasonable?' and finding a different way of checking the result;
- *justify your answers*; we hope that you have developed this habit — that you are always thinking of data or theory or evidence which backs up your assertions, and that your answers come out with the addition of 'because...'.

Finally, bear in mind that just as scientists, or science students, are constantly pushing back the boundaries of their knowledge as they discover answers to questions about the world around them, so they are also constantly improving their skills. They may be developing better communication skills, better mathematical skills, better experimental skills, or whatever. The message is clear: the voyage that you have embarked on by studying this course is not complete. Skills can always be improved, as any sports player knows only too well, but it takes continued practice to do this. And there are plenty of more advanced skills for you to tackle now that you have a wide range of skills under your belt, skills such as creativity and developing judgement, which you can choose to develop while studying future courses.

Objectives for Block 12

The objectives state what you should understand and what you should be able to do after studying the block.

The numbers of questions and activities that test each objective are given in italics.

Science content

1 Explain the meaning of, and use correctly, all the terms printed in **bold** in the text.

2 Outline and comment on evidence relating to the origin and early development of life on Earth. (*Activities 2.1–2.5*)

3 Use evidence from Section 2 to support or counter hypotheses about the origin of life on Earth. (*Activities 2.3–2.5*)

4 Discuss the general requirements for life as we know it on Earth, and for life elsewhere. (*Activity 3.1*)

5 Explain why certain planets and satellites are better targets than others for searches for extraterrestrial life as we know it. (*Questions 3.1 and 3.2*)

6 Outline the evidence for and against life now, and in the past, on Mars and Europa. (*Activities 3.2–3.6*)

7 Outline indirect methods of finding extrasolar planets, and the results to date. (*Questions 4.1–4.3*; *Activity 4.1*)

8 Outline and compare direct methods of finding extrasolar planets. (*Question 4.4*)

9 Outline methods of finding extrasolar life, and the results to date. (*Activity 4.3*)

Science skills

10 Develop a hypothesis, and specify steps to be taken in such a development. (*Activity 1.1*)

Communicating science skills

11 Read scientific articles not written specifically for S103, and extract and write down information from them for a variety of purposes. (*Activities 2.1–2.5, 3.1–3.6 and 4.1–4.3*)

12 Present medium-length written accounts based on more than one source including the evaluation of competing arguments. (*Activity 4.3*)

Mathematical skills

13 Insert values into given equations, and express answers in the appropriate units and to the appropriate number of significant figures. (*Question 4.1*)

14 Plot points on a graph and interpret the curve. (*Question 4.3; Activity 4.1*)

S103 Course Team

S103 *Discovering Science* was produced for the Science Faculty by a team drawn from many areas of the Open University. The full list of contributors to the course is printed in the *S103 Course Guide*.

Block 12 was produced for the S103 Course Team by the team of people listed below.

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Glossary for Block 12

Glossary entry headings that are followed by an asterisk (*) are terms that we expect you to be able to explain the meaning of, and use correctly, both during your study of the course and at the end of the course. (Note that the entries in this Glossary are *not* included in the *Course Glossary*.) Cross-references within entries to other Glossary entries (either in this Glossary or in the *Course Glossary*) are indicated by underlining.

adaptive optics* The technique in which the blurring effect of the Earth's atmosphere on telescope images is (partially) corrected by monitoring the atmosphere, and adjusting the optical layout of the telescope. This adjustment needs to be made many thousands of times per second.

astrometric technique* The technique of detecting planets by measuring the position of a star at various points in the star's orbit around the centre of mass of the planetary system.

astronomical unit (AU)* The mean distance of the Earth from the Sun. To three significant figures its value is 1.50×10^8 km.

centre of mass* In the context of planetary systems, the point around which the star and any planets orbit. The centre of mass of any system moves in the same way as would the whole system were it concentrated at the centre of mass.

chemical evolution* The synthesis in the early Earth of complex organic molecules from simple precursors. Subsequently, living cells became based on some of these complex molecules.

chemo-autotroph* Autotrophic prokaryotes that obtain energy by oxidizing inorganic compounds (such as H_2S), or that oxidize simple carbon compounds containing one carbon atom. They can live in the dark. Methanogens (among the Archaea) are one example.

extraterrestrial origin* (of life) The hypothesis that living organisms reached the Earth from an extraterrestrial source, and so did not originate on the Earth.

habitable zone This is the range of distances from a star within which an Earth-like planet would be habitable.

radial velocity technique* The technique of detecting planets by measuring the Doppler shifts in the spectral lines of the star they orbit, due to the motion of the star around the system's centre of mass.

reflecting telescope* A telescope in which light is collected by a large dish-shaped mirror (rather than by a lens).

search for extraterrestrial intelligence (SETI)* The search for life that has evolved to the point that it is 'technologically intelligent', rather as humans are. It has so far been conducted mainly through searching for radio signals.

universal common ancestor* The common ancestor from which all living organisms are descended.

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